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Scottish Universities Research & Reactor Centre

Investigation of Spatial and Temporal Aspects of Airborne Gamma Spectrometry

Report on Phase I Survey
Conducted April 1999

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EXECUTIVE SUMMARY

A project to investigate the spatial and temporal influences on Airborne Gamma-ray Spectrometry (AGS) has been commissioned by the Department of the Environment, Transport and the Regions (DETR) and other organisations. The field work has been divided into a number of phases to be undertaken under different seasonal conditions allowing evaluation of seasonal effects. The first phase of this project, reported here, involved a survey of a 20×30 km region of the Solway Firth with a 250 m line spacing, with an additional inset 6×11 km region with a 50 m line spacing around Rockcliffe Marsh. The survey employed a 16 litre NaI(Tl) detector with supplementary measurements made with a pair of externally mounted thin Ge (LoAx) detectors. A total of 41 hours was flown on survey, with some 21300 NaI(Tl) spectra recorded with 3 s integration times, and 18700 with 2 s integration time. 5300 spectra were recorded from the LoAx detectors, 2700 of which were recorded with both detectors operating.

Gross count rates for windows in the NaI(Tl) spectra, corresponding to ^{137}Cs, ^{60}Co, ^{40}K, ^{214}Bi, ^{208}Tl and the total γ-ray dose rate, were determined for each spectrum. Backgrounds determined from measurements made over open water were subtracted, interferences between spectral components stripped out, and altitude and sensitivity calibration factors applied. Maps for the resulting calibrated distribution of ^{137}Cs, ^{40}K, ^{214}Bi, ^{208}Tl, and γ-ray dose rate were produced.

^{137}Cs activities up to few hundred kBq m^{-2} are observed on salt marsh environments, as a result of historic marine discharges from the Sellafield reprocessing plant in Cumbria. These salt marsh features had largely been observed in the 1992 Chapelcross survey. However, there are some differences compared to the earlier data; in particular Burgh Marsh has significantly eroded, Rockcliffe Marsh and salt marshes near Annan are more pronounced, and small features register better primarily due to the higher spatial resolution of this survey.

The distribution in the environment of ^{40}K, ^{214}Bi and ^{208}Tl reflect local geology and soils, with relatively high levels of ^{40}K on estuarine mud and very low levels of all these naturally occurring radionuclides over the peat wetlands.

Uncorrected interferences from ^{41}Ar and ^{16}N gaseous discharges from the Chapelcross power station results in apparently high ^{40}K, ^{214}Bi and ^{208}Tl activity in the immediate vicinity of the plant.

There are relatively high levels of ^{214}Bi associated with some railway sidings to the northwest of Carlisle, probably relating to the use of material enhanced in uranium, for example industrial slag, in the construction of the line.

Gaseous radon is a precursor for ^{214}Bi, and the high mobility of this gas can lead to local disequilibria. Difficulties were experienced during this survey with correctly accounting for the effects of radon migration on some days.

Apart from the Chapelcross signals, the highest dose rates are from the ^{137}Cs contaminated salt marshes, particularly around Moricambe Bay to the NE of Silloth. The wet peat areas, which were observed to have very low natural activity levels, have very low dose rates similar to background levels over open water.

The higher resolution survey has produced maps with much greater spatial resolution, easily identifying features with spatial dimensions of 50 m, compared to 200 m for the lower resolution survey data. The higher resolution data clearly shows river channels, and small stream and standing water on the salt marshes. Compared with earlier surveys the salt marshes near Annan are much more pronounced, possibly due to the closer line spacing of this survey picking up these relatively small features, and Burgh Marsh has noticeably eroded.

True colour composite and thematic maps have been produced from LandSat TM data for this area. The features observed in these images correspond very well with the radiometric data. In particular, the peat wetlands are well registered and correspond to the low activity levels in the radiometrics and the land classification and boundaries of ^{137}Cs distribution in the marine interfaces demonstrates that both radiometrics and contemporary imaging give consistent information about the position of features (eg: Burgh Marsh and river channels) in a dynamic coastal environment.

The data collected in this survey will, later in the project, be used in a comparison with data collected from the same area in previous work and in later phases of this project under different seasonal conditions. This will enable the effect of long and short term temporal variations and the effect of line spacing to be quantified using geostatistical methods and inventory analyses.

CONTENTS

1. INTRODUCTION

This report documents the results of an airborne gamma ray survey conducted by the Scottish Universities Research and Reactor Centre (SURRC) between 20 and 28 April 1999 in NW England and SW Scotland. The survey was carried out in the first phase of a wider project commissioned by the Department of the Environment, Transport and the Regions (DETR) and other organisations.

1.1 Airborne Gamma Spectrometry (AGS)

The AGS method is highly appropriate for large scale environmental surveys of areas of potentially contaminated ground. The methodology for aerial surveys is well established (Sanderson *et al.*, 1994a, 1994b), and has been used by the SURRC team for a variety of purposes including environmental assessments of contamination (Sanderson *et al.*,1990a, 1990b); Chernobyl fallout mapping (Sanderson *et al.*, 1989a, 1989b, 1990c, 1994c); baseline mapping around nuclear establishments (Sanderson *et al*., 1990d, 1992, 1993b, 1994d); the effects of marine discharges on coastal environments (Sanderson *et al.*, 1994c); epidemiological studies (Sanderson *et al.*, 1993a); and radioactive source searches (Sanderson *et al.*, 1988, 1991). In addition, the technique has been used by airborne survey teams from Scandinavia, Germany, France and other countries.

By operating suitable spectrometers from low flying aircraft, in this case a helicopter, it is possible to map the distribution of γ-ray emitting radionuclides at ground level. This has a number of advantages when compared with conventional methods. High sensitivity 16 litre NaI(Tl) detectors installed in the aircraft are capable of making environmental radioactivity measurements every few seconds, thus providing a sampling rate some 10^2-10^3 times greater than other approaches. The radiation detector averages signals over fields of view of several hundred metre dimensions, resulting in an area sampling rate some 10^6-10^7 times greater than ground based methods. A sequence of γ-ray spectra, geographic positioning information and ground clearance data are recorded simultaneously, and are used to quantify levels of individual radionuclides and the general γ-dose rate. The high mobility of the aircraft is also advantageous, as is its ability to operate over varied terrain, unimpeded by ground level obstacles or natural boundaries. Moreover, the remote sensing nature of the measurements minimises exposure of survey teams to surface contamination or radiation hazards. This results in a practical means of conducting surveys with total effective coverage, which can be used for rapid location of point sources or areas of radioactive contamination. This has important implications for environmental radioactivity studies, especially where there are time constraints, and is highly significant in emergency response situations.

The SURRC team has also utilised a combined detector system for airborne radionuclide monitoring. This consists of a detector containing 16 litres of NaI(Tl) installed inside the aircraft, and two cryogenically cooled germanium (Ge) semiconductor detectors mounted on the outside. Whilst the use of NaI detectors is well established and used frequently in airborne surveys, the use of a coupled pair of low energy Ge detectors outside the aircraft is relatively new. The Ge detectors have a much higher energy resolution than the NaI(Tl) scintillator detector, and so are able to identify the nuclides contributing to the gamma ray spectrum, particularly where complex fission product sources are present. However, they are considerably less sensitive than NaI(Tl) requiring the use of longer integration times with a resulting loss of spatial resolution in all but the most active environments. In the current work a pair of thin Ge (LoAx) detectors was used, these are particularly sensitive to low energy γ-rays, to study ^{241}Am distribution. The low energy γ-rays associated with this isotope have a very short penetration depth, resulting in the need for an external mounting and low altitude survey.

1.2 Project Aims

The aims of the overall project, of which the work reported here are the results of the first phase of field work, are to investigate the spatial and temporal influences on airborne gamma ray spectrometry (AGS) with particular reference to the effects of (i) line spacing, (ii) survey ground clearance, (iii) seasonality, and (iv) environmental change. Supplementary collaborative work involving experimental assessment of digital photogrammetry and satellite imagery is also taking place with scientists at the University of Glasgow and the University of Stirling respectively.

To investigate the spatial and temporal influences on AGS, surveys of several regions in NW England and SW Scotland are planned, the results from the first set of these measurements being presented here. These areas will be surveyed using a range of line spacings from 50 m to 2.5 km with sub-sampling of these data sets to provide data for larger line spacing. To investigate seasonal effects, the field work has been divided into a number of phases to be undertaken under different seasonal conditions. The area chosen for this study exhibits a range of radiation environments due to natural variations, Chernobyl fallout and Sellafield discharges; and encompasses wide variations in landscape with mountainous terrain, moorland, forest, pasture and estuarine environments. The SURRC AGS team have conducted radiometric surveys of parts of the area covered in this project on several occasions over a ten year period (Sanderson *et al.*, 1989a, 1990d, 1994c), allowing evaluation of changes in the environment over a more extended period.

This report contains the results of the first phase of field work, conducted in April 1999, with a review of the calibration factors following resampling of the calibration pattern on Caerlaverock Merse. The data from this work is presented in the form of maps of the distribution of ^{137}Cs, ^{40}K, ^{214}Bi, ^{208}Tl and the γ-ray dose rate in areas A and B. LandSat images and thematic maps prepared by P.A. Atkin and A.N. Tyler of the University of Stirling are also presented.

The data from this field work are a resource that will be used, in conjunction with data collected in earlier surveys and from later phases of this project, for spatial and temporal analyses at later stages in the project.

2. SURVEY DETAILS

2.1 Instrumentation

The system used was based on a high volume 16 litre thallium doped sodium iodide (NaI(Tl)) spectrometer operated inside the aircraft. Supplementary measurements were also made using a pair of thin Ge (LoAx) detectors operated outside the aircraft, with the specific aim of evaluating the feasibility of mapping ^{241}Am in salt marsh environments from aircraft using such detectors.

The equipment consisting of the combined system of NaI(Tl) and Ge detectors and associated instrumentation was installed in a twin engine AS355 Squirrel helicopter at Cumbernauld airport, North Lanarkshire, and tested on the 19 April prior to deployment for the survey. The NaI(Tl) spectrometer was loaded inside the aircraft, whilst the two Germanium detectors were mounted on the outside. Camera mounts were fitted inside the helicopter to allow digital photogrammetry and video imagery to be collected for exploratory investigations of the use of photographic material along with radiometric survey data.

With the exception of the first two days of survey when autonomous Global Positioning System (GPS) data were used, two differential GPS (DGPS) systems were used for navigation and locating the data. A hand held Garmin unit was pre-programmed to display an indication of position relative to each planned flight line to the pilot, whilst a Navstar unit attached to the instrument rack fed positional data with a precision of ±5-10 m to the data recording system.

2.2 Survey Parameters

The first phase of the project involved surveys of two areas in the Inner Solway (areas A and B as shown in Figure 2.1). Area A, enclosing a 11×6 km region bounded by OS coordinates NY260590-NY370650, was flown at 50 m line spacing. This area was expanded 1 km west of the originally planned 10×6 km region to include all of Burgh Marsh, which was observed to have eroded significantly since earlier surveys. The larger area B, enclosing a 30×20 km region bounded by OS coordinates NY100500-NY400700, was flown at 250 m line spacing. Both areas were flown with survey lines orientated east-west.

In addition, a calibration manoeuvre and a series of tie lines were flown. The calibration manoeuvre, conducted on two separate occasions, consisted of measurements conducted while hovering at a series of altitudes above a calibration pattern laid out on the salt marsh at Caerlaverock, Dumfries and Galloway. Soil cores were later collected from the marsh for analysis in the laboratory. The tie lines were flown in a north-south at a range of altitudes covering all the areas due for survey during this phase of the project, and will be reflown during later survey phases to ensure comparability of data.

Operations were conducted from a cottage at Allerbeck Farm, near Eaglesfield in Dumfries and Galloway, slightly to the north of the survey areas, where facilities were provided for refuelling the aircraft and initial data analysis. The detector system performance (gain, resolution and sensitivity) was checked at the start of each day, and trimmed as necessary. Background measurements were made at high altitude and over the sea, with background observations for the majority of flight lines. All data were backed up onto ZIP disks at the end of each day, and restored to a separate computer for verification. Spectral data were replayed from restored data to verify backups prior to deletion of primary data from the logging computer.

Summary files, consisting of gross count rates for 6 windows in the NaI(Tl) spectra (corresponding to ^{137}Cs, ^{60}Co, ^{40}K, ^{214}Bi, ^{208}Tl and total γ-dose rate), were produced from the data after each survey flight. Some initial analysis was conducted in the field to identify any problems that may have occurred with the spectrometry system, and to facilitate the re-surveying of any areas as necessary.

The weather on the first few days of operation was less than ideal for survey work, being overcast with heavy rain at times, though it did improve later in the survey period. Survey flights over mud flats were conducted near low tide, so the first flight of the day was started in the mid-late morning. A total of 41 hours were flown on survey, with 42.5 hours used in the project including transits from Cumbernauld.

The less demanding task (area B at 250 m line spacing) was flown first due to poor weather conditions, initial lack of DGPS and to enable the pilot to familiarize himself with the task. The survey started at the south east corner of the survey area (NY400500), and progressed northwards. The northern edge of this area includes the Chapelcross Nuclear Power Station. Permission was gained to enter the air exclusion zone up to the perimeter fence, and as a result four circuits of the plant were conducted and the ^{41}Ar plume was mapped for several km downwind. The eastern side of the area includes part of Carlisle. Permission was gained to survey the urban areas at low altitude, and this was conducted in a single flight (using north-south flight lines) at the end of the survey to minimize disturbance to the populace (local media was used to inform the populace of the survey and the low flying aircraft). Area B was surveyed between 20th and 24th April, and on the 28th when Carlisle was surveyed together with sections of repeat flying to fill in gaps in survey data. This area was surveyed using a 3 s integration time for the NaI(Tl) spectrometer and 6 s for the LoAx detectors.

The smaller region (area A at 50 m line spacing) was flown in a progressive spiral pattern in order to avoid excessively tight turns at the end of each leg. After each east to west leg the following leg was flown west to east 350 m further north, and the following east to west leg 300 m south. Each spiral covered a strip 700 m $\times$ 11 km, and was programmed as a single route in the DGPS system used for navigation. This area was surveyed between the 25th and 27th April using a 2 s integration time for the NaI(Tl) spectrometer. No LoAx data were recorded during this period.

Tie lines, oriented north south, were flown at five altitudes. A 30 km line between Bowness Common (NY200600) and Bassenthwaite Lake (NY200300) was flown at 75 and 125 m. A 10 km line between Bowness Common and Wedholme Flow (NY200500) was flown at 30, 50 and 250 m. These were flown on the morning of the 27th April using a 3 s integration time for the NaI(Tl) detector, and with one LoAx detector using a 6 s integration time.

In total some 21300 NaI(Tl) spectra were recorded with 3 s integration times, and 18700 with 2 s integration times. 5300 spectra were recorded from the LoAx detectors, of which 2700 were recorded with both detectors operating. Figure 2.2 shows the flight track recorded by the Garmin GPS system during the survey.

2.3 Review of Stripping Ratios and Calibration

Prior to deployment in April 1999 the stripping factors associated with the 16 litre NaI(Tl) detector pack, were measured. A series of spectra, each with a 30 s integrating time, were recorded with the detector pack placed above a set of concrete calibration pads with 5 sheets of perspex (equivalent to a 50 m air path) placed between the detector and the pad, and another 5 sheets placed on top of the detector. Three concrete pads doped in ^{40}K, ^{238}U series isotopes and ^{232}Th series isotopes were used, together with an undoped pad for background measurements. Spectra for anthropogenic isotopes were also recorded by placing a set of wooden sheets doped with ^{137}Cs or a ^{60}Co point source on the background pad. Files of net count rates in each of the windows used for radiometric measurements during the survey were produced, and stripping factors determined from the ratios of mean net counts in each set of spectra. The stripping factors determined by this means are given in Appendix A, Table A.4.

The detector calibration was confirmed by a calibration manoeuvre at Caerlaverock Merse, which has been used for detector calibration during previous surveys (Sanderson *et al.*, 1992, 1994c). This manoeuvre, which was conducted on two occasions during the survey, consists of recording a series of spectra whilst hovering at altitudes ranging from almost touching the surface to approximately 100 m ground clearance over the centre point of a calibration pattern consisting of an expanding series of hexagons (Tyler *et al.*, 1996a).

The Caerlaverock calibration site was resampled on the 27th April, with 25 cores collected from the hexagonal pattern excluding the innermost ring. The location of each point in the pattern was determined using a 1 m precision DGPS system. The cores were frozen upon return to SURRC for later analysis. The activity profile of each core was measured by use of a core scanner consisting of a 50% efficiency Ge (GMX) detector and a motorised trolley. A lead shield was constructed around the detector with a 2 cm wide aperture in front of the crystal. Each core was placed on the trolley, which was moved in front of the aperture in 2 cm steps, with a spectrum recorded for each step. This arrangement was calibrated by cutting some of the cores into 2 cm slices, which were dried, ground and homogenised before being placed in standard 40 ml volume sample geometries for counting by well shielded, calibrated Ge detectors. The ^{137}Cs depth profiles for the cores are given in Appendix B, Figures B.1-B.3.

The data was used to determine the ^{137}Cs depth profile at each location, from which a mean mass depth of 15.7±1.2 g cm^{-2} (compared with 13.2±2.1 g cm^{-2} in February 1992) was determined, resulting from an average sedimentation rate of 0.3 g cm^{-2} a^{-1}. The ^{137}Cs activity, in kBq m^{-2}, for each core was calculated from the total inventory of the core, and the corresponding activity at a ground clearance of 100 m was calculated as 60.8±9.8 kBq m^{-2} by applying a weighting function to each shell of the calibration pattern (Tyler *et al.*, 1996a). This is within one standard deviation of the value determined in 1992 (77.2±8.2 kBq m^{-2}) having accounted for radionuclide decay. The mean ^{137}Cs mass depth and activity per unit area for each core are given in Appendix B, Table B.1.

Data from the calibration manoeuvre were used to determine exponential altitude correction coefficients, to normalise all data to a ground clearance of 100 m. After applying these coefficients, a calibration constant was determined to give a mean activity in accord with the value determined from the sampling pattern for ^{137}Cs. The potential effects of variations in mass depth distribution within the survey area should be considered when interpreting quantitative estimates of activity per unit area. Theoretically derived calibration constants were used for the naturally occurring ^{40}K, ^{214}Bi and ^{208}Tl. These calibration factors were used for the analysis of the survey data sets, and are given in Appendix A, Table A.5.

Six cores additional were collected on the 28th April from an east-west transect on Rockcliffe Marsh. Additional cores were collected on 30th April from Glasson Moss, Burgh Marsh and Newton Marsh, together with in-situ gamma spectrometry measurements using a 3×3" NaI(Tl) detector at these sites and Rockcliffe Marsh. The data from these measurements have yet to be analysed.

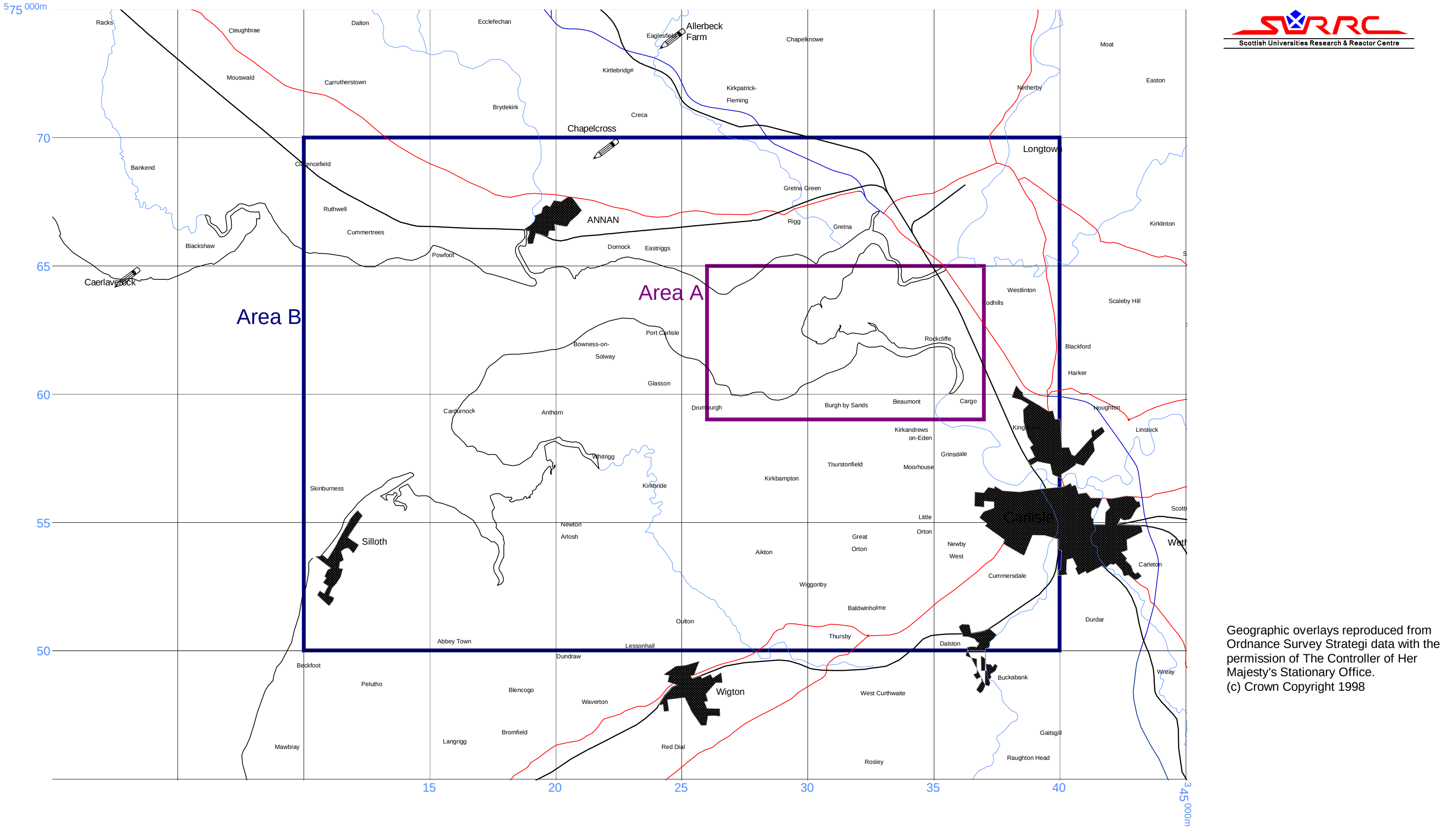

Figure 2.1: Map showing location of survey areas A and B

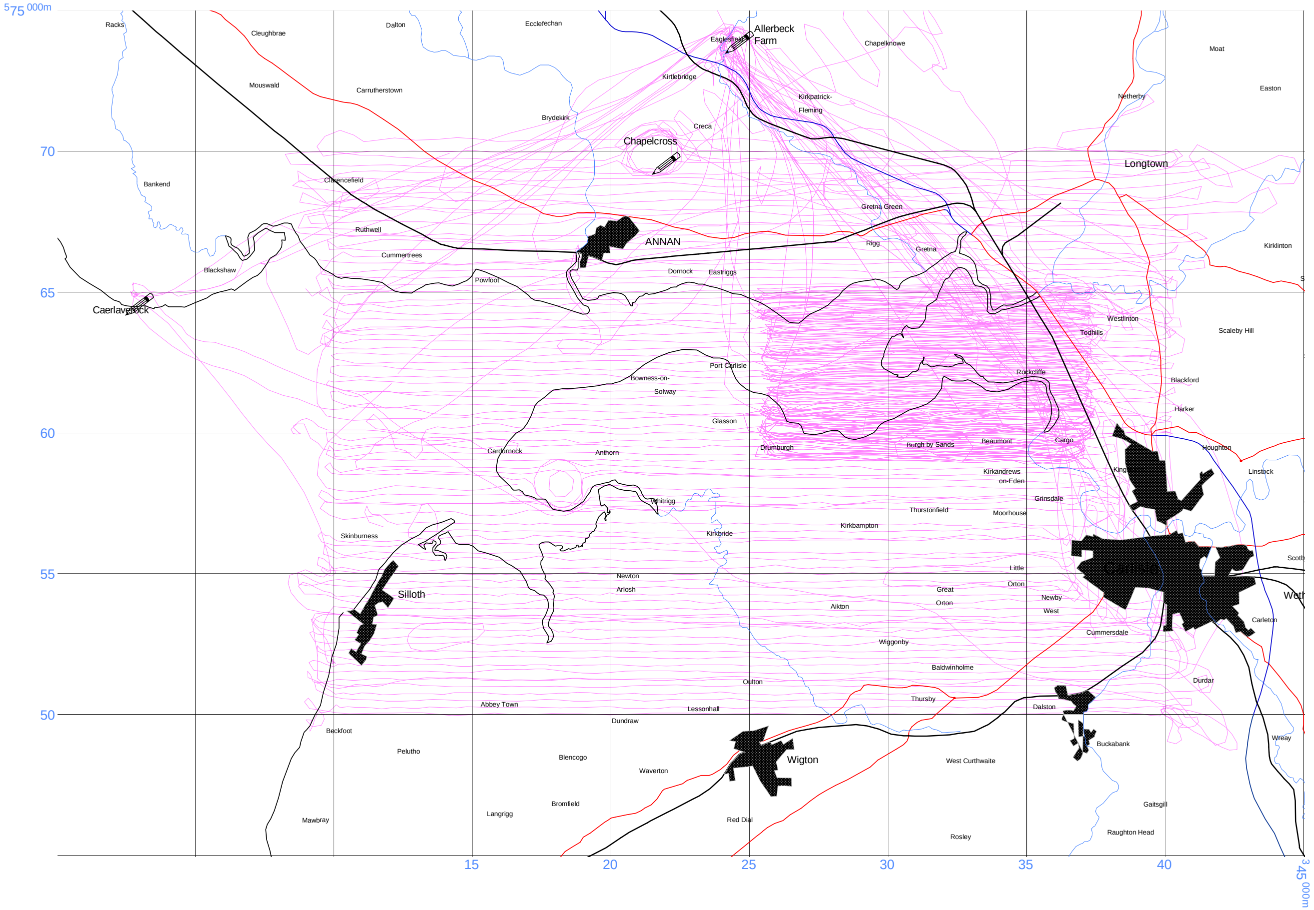

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Figure 2.2: Plot of flight tracks recorded by the Garmin GPS system

3. RESULTS AND DISCUSSION

3.1 NaI(Tl) Data

A new set of summary files was compiled from the data recorded, excluding those sections of the data set recorded at high altitude, outside the survey area or not on a survey line. These new files contain data from 16356 spectra with a 3 s integration time, and 16314 spectra with a 2 s integration time. It was observed that a large gain shift had occurred on the final day of the survey (April 28th), and the data recorded on this day were re-integrated using a set of windows shifted to account for this reduced gain.

Daily background values were determined from spectra recorded over open water (usually at the western end of most flight lines) or at an altitude in excess of 400 m. These background values are tabulated in Appendix A. The background values for the data recorded on the 20th April are observed to be significantly higher than those recorded later in the survey, probably due to high radon levels in the atmosphere that day. The reduced detector gain on the 28th probably contributes to the higher background in that data set. Files containing net count rates were produced by subtracting the background values recorded on that day.

Calibration and altitude correction factors, determined from data collected during the calibration manoeuvres at Caerlaverock Merse and the activity profiles determined from the cores collected (see section 2.3), were used to produce a data set consisting of the position of each measurement and calibrated activities in kBq m^{-2} for ^{137}Cs, Bq kg^{-1} for the naturally occurring ^{40}K, ^{214}Bi and ^{208}Tl, and mGy a^{-1} for the γ-ray dose rate.

Problems were experienced in subtracting the background (particularly in the ^{214}Bi channel) from the data recorded on the 20th April, probably as a result of a large radon anomaly. The data presented here still contain a few minor anomalies, in the form of lines oriented east-west at slightly elevated or reduced activity, resulting from incorrect background subtraction. There were additional problems obtaining stripped count rates for the data recorded on the 28th April that were consistent with previous measurements as a result of the low detector gain, this problem has yet to be resolved and this data is excluded from the results presented here.

The data for each area was mapped by plotting the calibrated data for each point, and using an inverse power distance weighting function to smooth the data to interpolate between these points. Figures 3.1-3.10 show the resulting maps for the distribution of ^{137}Cs, ^{40}K, ^{214}Bi, ^{208}Tl activity and γ-ray dose rate for the two survey areas.

3.1.1 ^{137}Cs Distribution

The radiometric map of ^{137}Cs in the larger area B is shown in Figure 3.1, with the corresponding map for the smaller area A shown in Figure 3.2. The activity is plotted on a logarithmic scale comparable to earlier surveys (Sanderson *et al* 1992, 1994c), although it is calibrated to the estuarine rather than terrestrial environment. The earlier surveys had shown that the calibration to the salt marsh results in an overestimation of the activity in terrestrial environments.

The salt marshes, particularly Skinburnness and Newton Marshes, NE of Silloth, the Rockcliffe and Burgh Marshes in the Inner Solway, and the confluence of the River Annan and the Solway Estuary, show ^{137}Cs activities up to a few hundred kBq m^{-2}. This activity is the result of historic marine discharges from the Sellafield reprocessing plant in Cumbria.

These salt marsh features had largely been observed in the 1992 Chapelcross survey (Sanderson *et al.*, 1992). However, there are some differences compared to the earlier data; in particular Burgh Marsh has significantly eroded, Rockcliffe Marsh and salt marshes near Annan are more pronounced, and small features register better primarily due to the higher spatial resolution of this survey.

The activity distribution is much more highly defined in the 50m line spacing area A survey than in the corresponding section of the 250m line spacing area B survey.

The changes in these features, and comparisons between the two data sets collected on this survey, will be investigated more fully later in the project.

3.1.2 ^{40}K Distribution

Figures 3.3 and 3.4 show the levels of ^{40}K for areas B and A respectively. The levels of ^{40}K in the environment are a result of local geology and soils. There are relatively high levels on estuarine mud and very low levels over the peat wetlands of Solway Moss, Nutberry Moss, Priestside Flow, Glasson Moss, Bowness Common and Wedholme Flow. Apparently high ^{40}K activity in the immediate vicinity of the Chapelcross power station are a result of uncorrected interferences from ^{41}Ar (1295 keV), the peak for this isotope in the NaI(Tl) spectra slightly overlaps with the peak from ^{40}K. The ^{41}Ar is formed by neutron activation of ^{40}Ar in the atmosphere, and is discharged from the reactors.

3.1.3 ^{214}Bi Distribution

Figures 3.5 and 3.6 show the levels of ^{214}Bi for areas B and A respectively. ^{214}Bi is a nuclide in the natural U decay series, and is also largely a result of local geology. Gaseous radon is a precursor for this nuclide, and the high mobility of this gas can lead to local disequilibria. Difficulties were experienced during this survey with correctly accounting for the effects of radon migration on some days. Some minor linear features oriented east-west, resulting from incomplete background subtraction, are still evident in the area B map.

These maps also show low activity over the peat wetlands. There are very high signals associated with interferences from ^{16}N (6.13 MeV) and direct shine from the Chapelcross power station. There are relatively high levels of ^{214}Bi associated with some railway sidings to the northwest of Carlisle, probably relating to the use of material enhanced in uranium, for example industrial slag, in the construction of the line.

3.1.4 ^{208}Tl Distribution

Figures 3.7 and 3.8 show the levels of ^{208}Tl due to the natural Th decay series for areas B and A respectively. The ^{208}Tl distribution also shows the very low activity levels over the peat wetlands observed in the other natural channels. There is also a strong signal associated with ^{16}N interferences from discharges from the Chapelcross reactors.

3.1.5 Gamma-ray Dose Rate Distribution

Figures 3.9 and 3.10 show the γ-ray dose rate in areas B and A respectively.

The ^{41}Ar discharge plume from the Chapelcross power station, along with ^{16}N and direct shine close to the site, form a high dose rate to the north of the survey area. The data is calibrated to a source on the surface, whereas these are airborne sources. This would result in an apparently enhanced dose rate compared to signals from terrestrial sources. In addition, these signals will be strongly dependant on weather conditions which would affect the plume direction, range and coherence.

Apart from the Chapelcross signals, the highest dose rates are from the ^{137}Cs contaminated salt marshes, particularly around Moricambe Bay to the NE of Silloth. The wet peat areas, which were observed to have very low natural activity levels, have very low dose rates similar to background levels over open water.

3.1.6 Comparison between survey areas

The general features in this area are shown in both sets of maps produced from this survey, but the higher resolution survey of area A reveals much greater detail. The high resolution survey is sensitive to features of the order of 50 m, whereas the lower resolution survey has a minimum feature size of the order of 200 m.

Both data sets clearly show major river channels, with minor streams and standing water on the salt marshes evident in the high resolution data set. The clearly defined river channels appear to be in slightly different locations than given by the digital OS maps. The satellite imaging (section 3.4) shows the same features in the same locations using independent coordinate transformation indicating that these river channels have indeed shifted since the OS maps were produced. It was noted that some of the salt marshes, particularly Burgh Marsh, were being eroded at the time of survey.

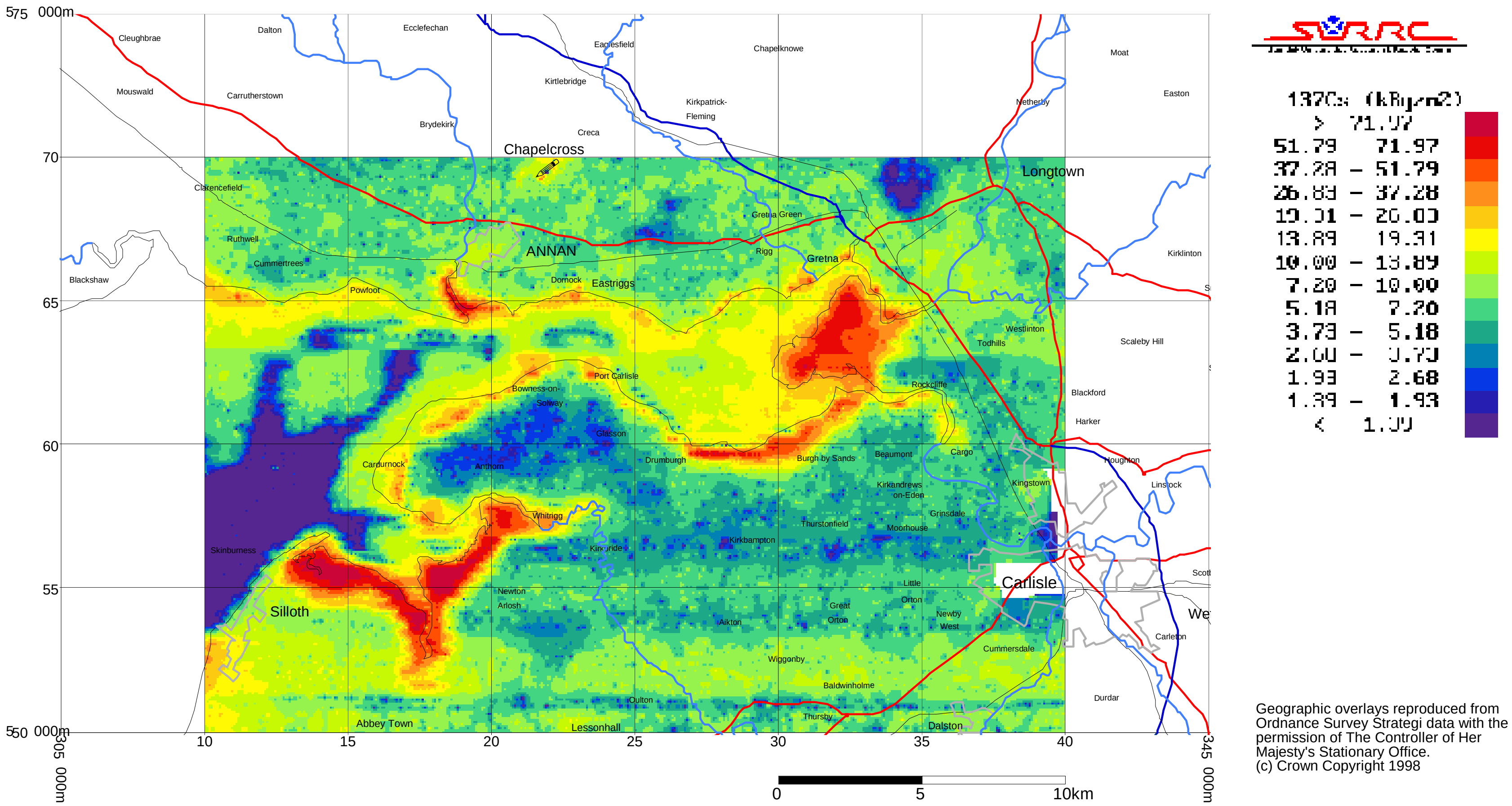

Figure 3.1: ^{137}Cs activity distribution in area B

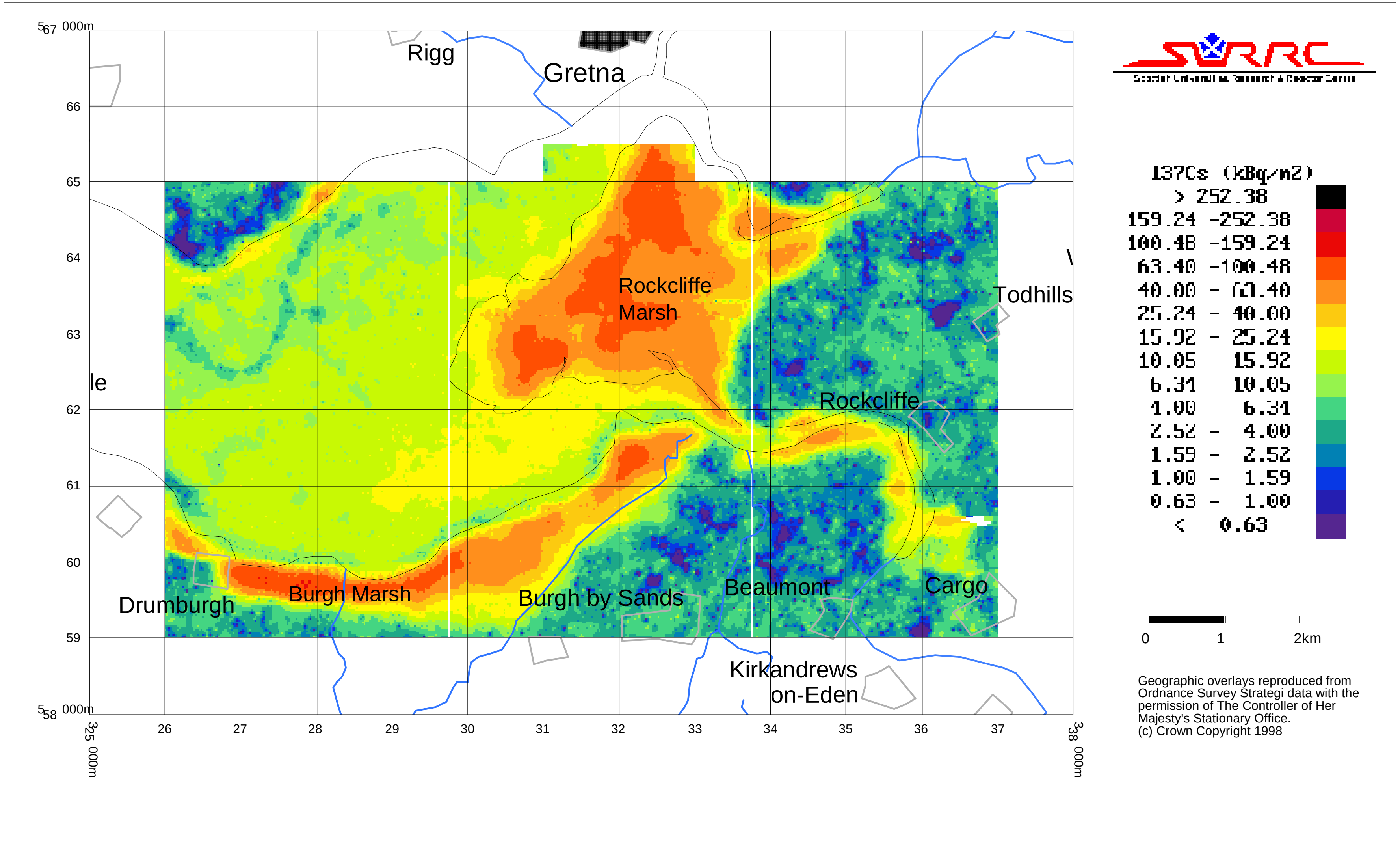

Figure 3.2: ^{137}Cs activity distribution in area A

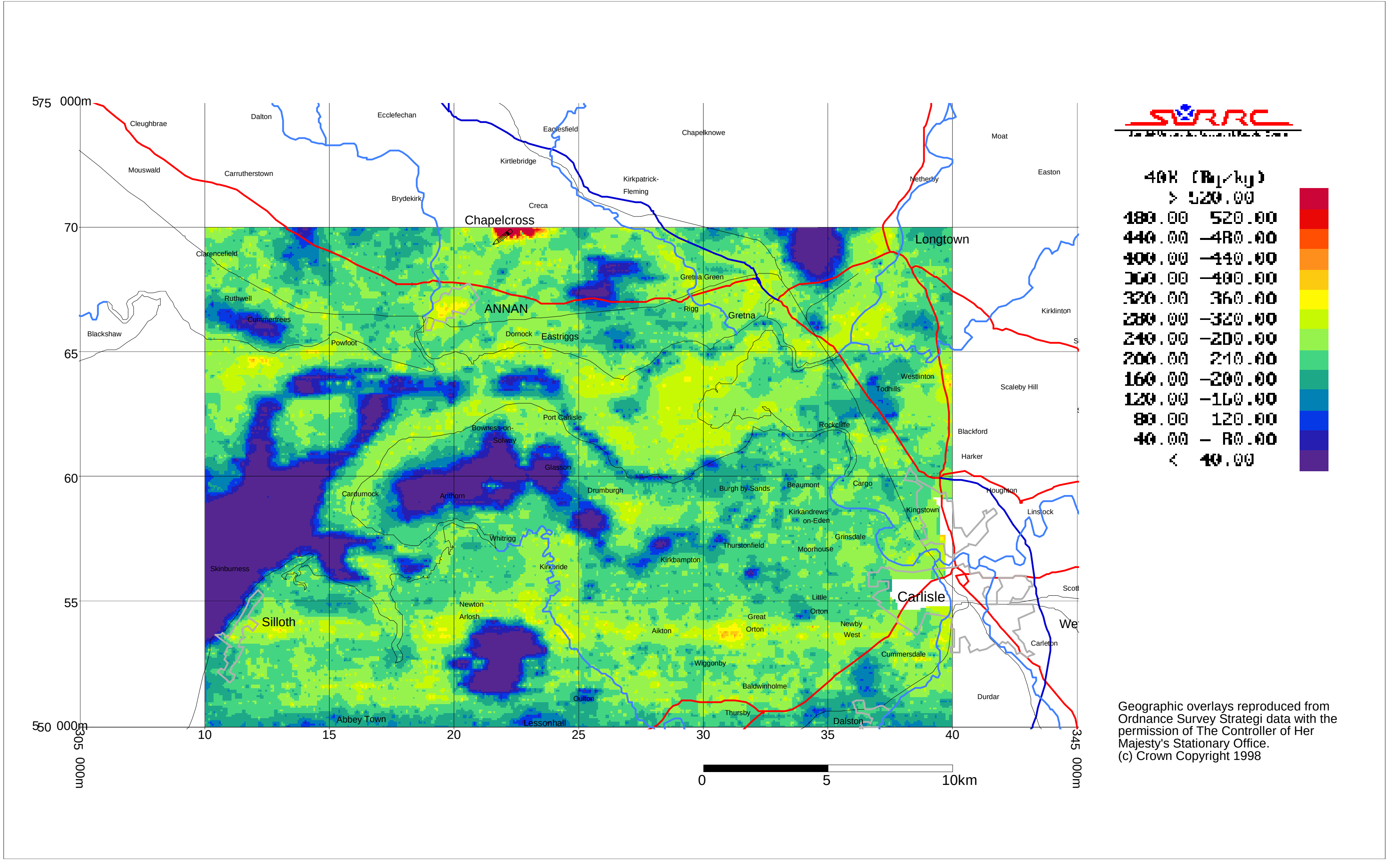

Figure 3.3: ^{40}K activity distribution in area B

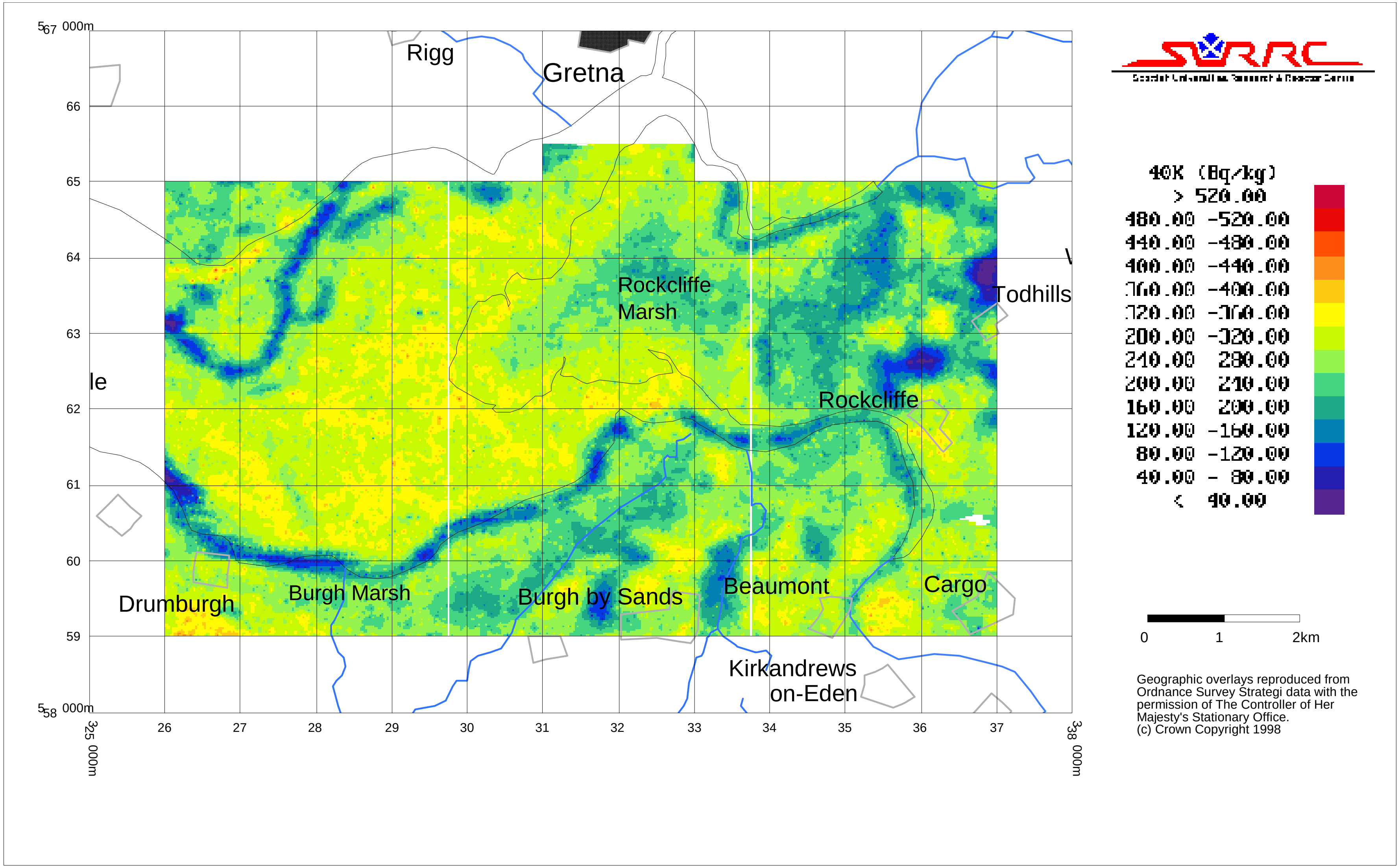

Figure 3.4: ^{40}K activity distribution in area A

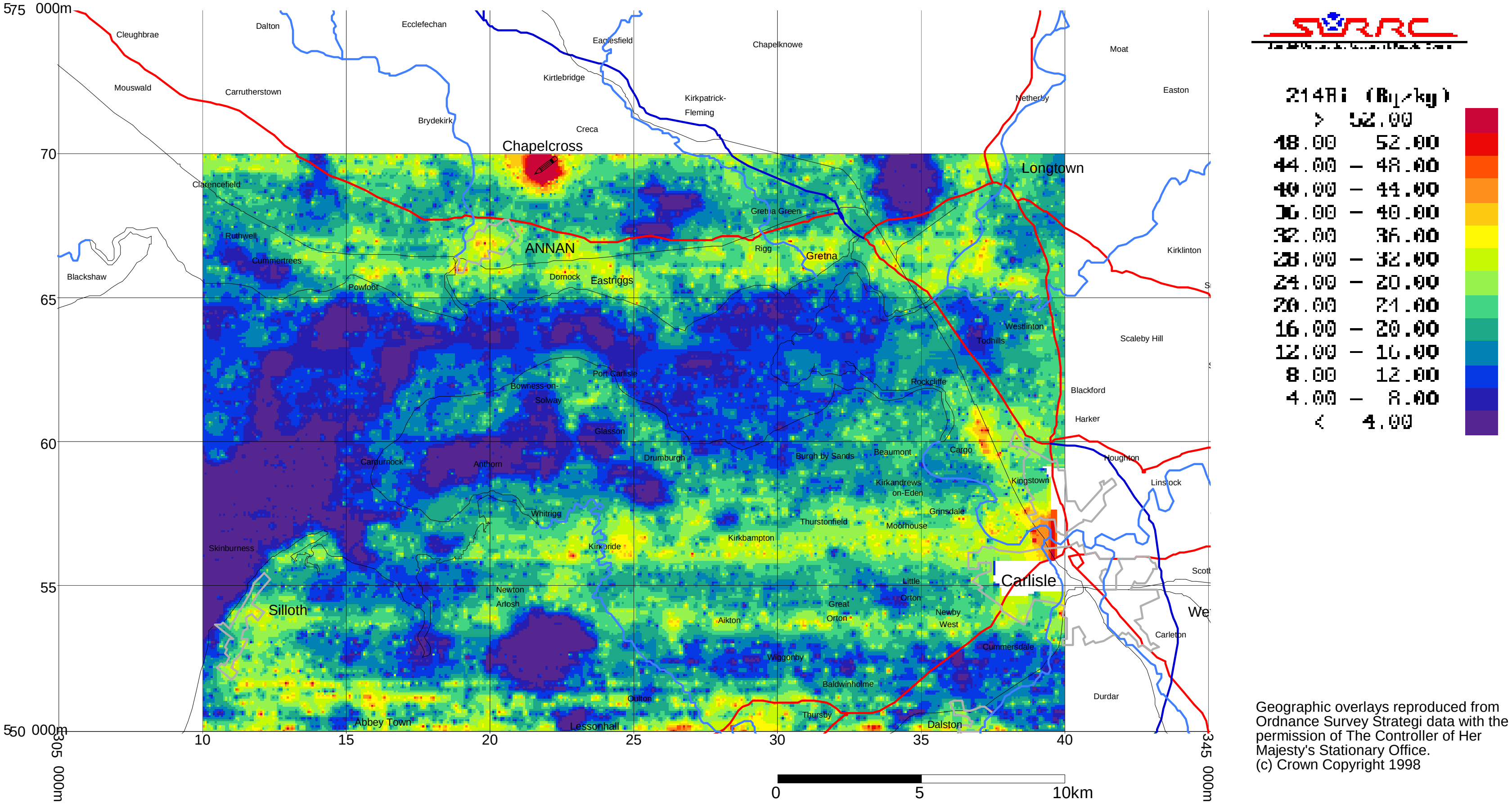

Figure 3.5: ^{214}Bi activity distribution in area B

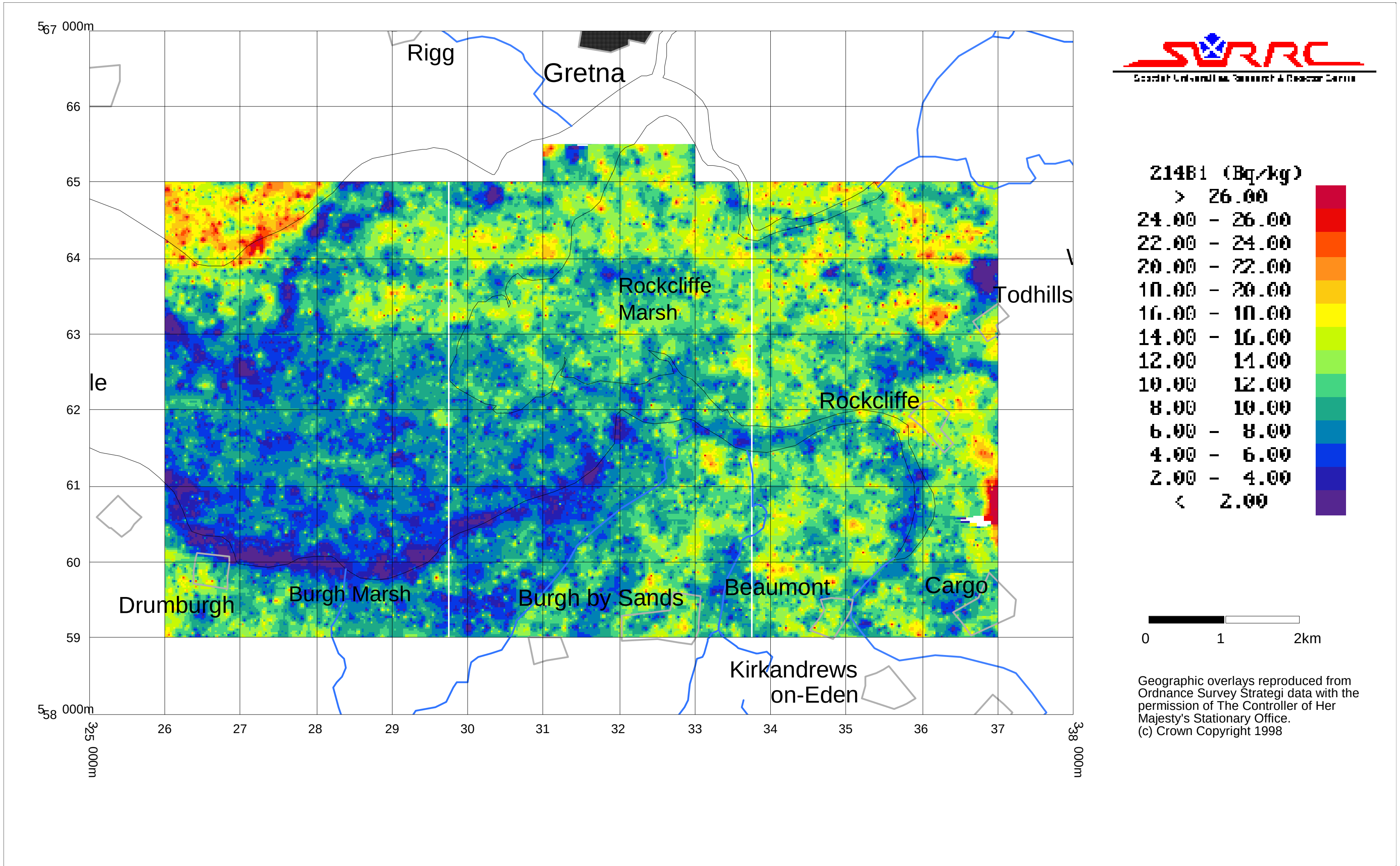

Figure 3.6: ^{214}Bi activity distribution in area A

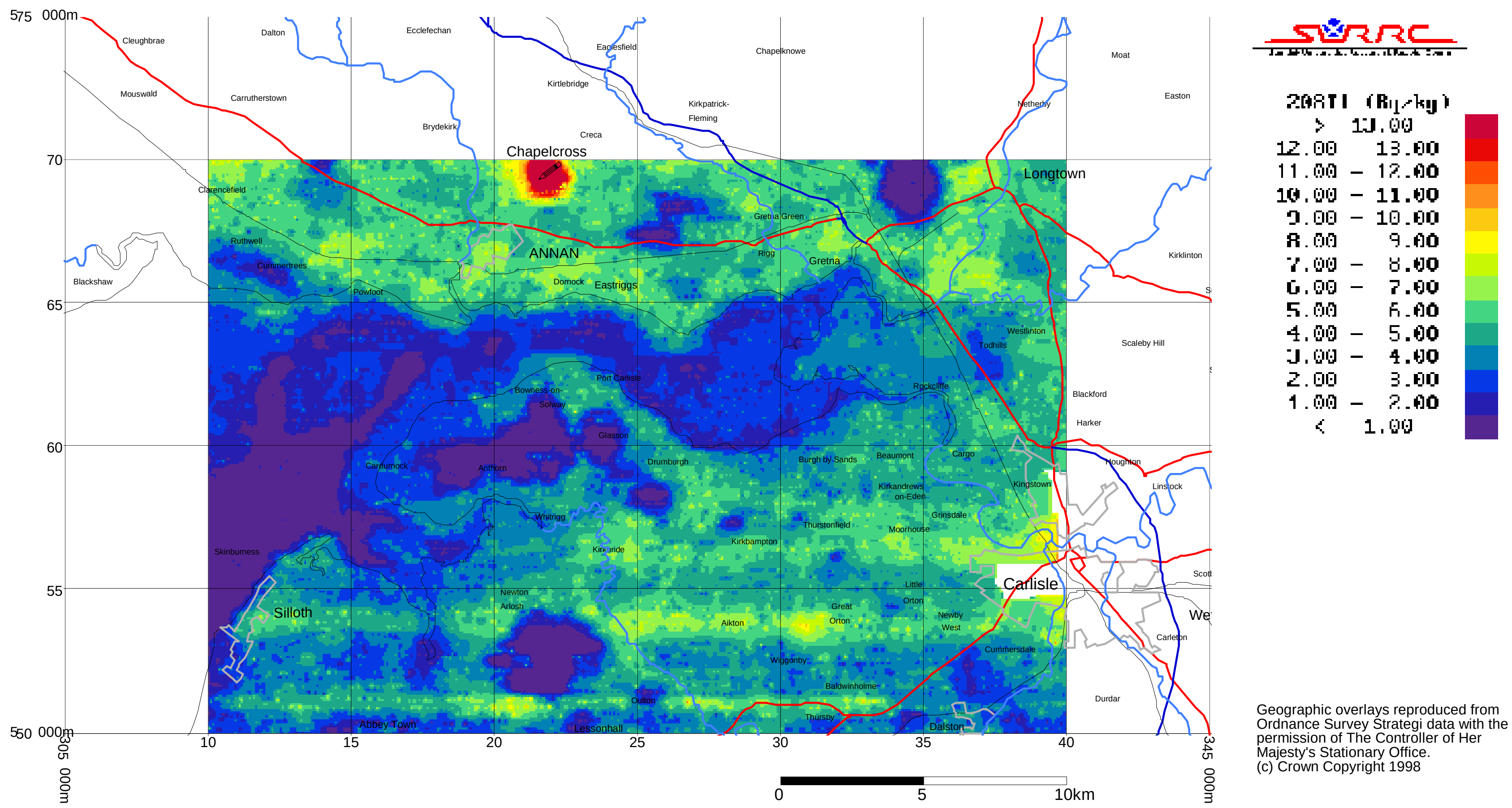

Figure 3.7: ^{208}Tl activity distribution in area B

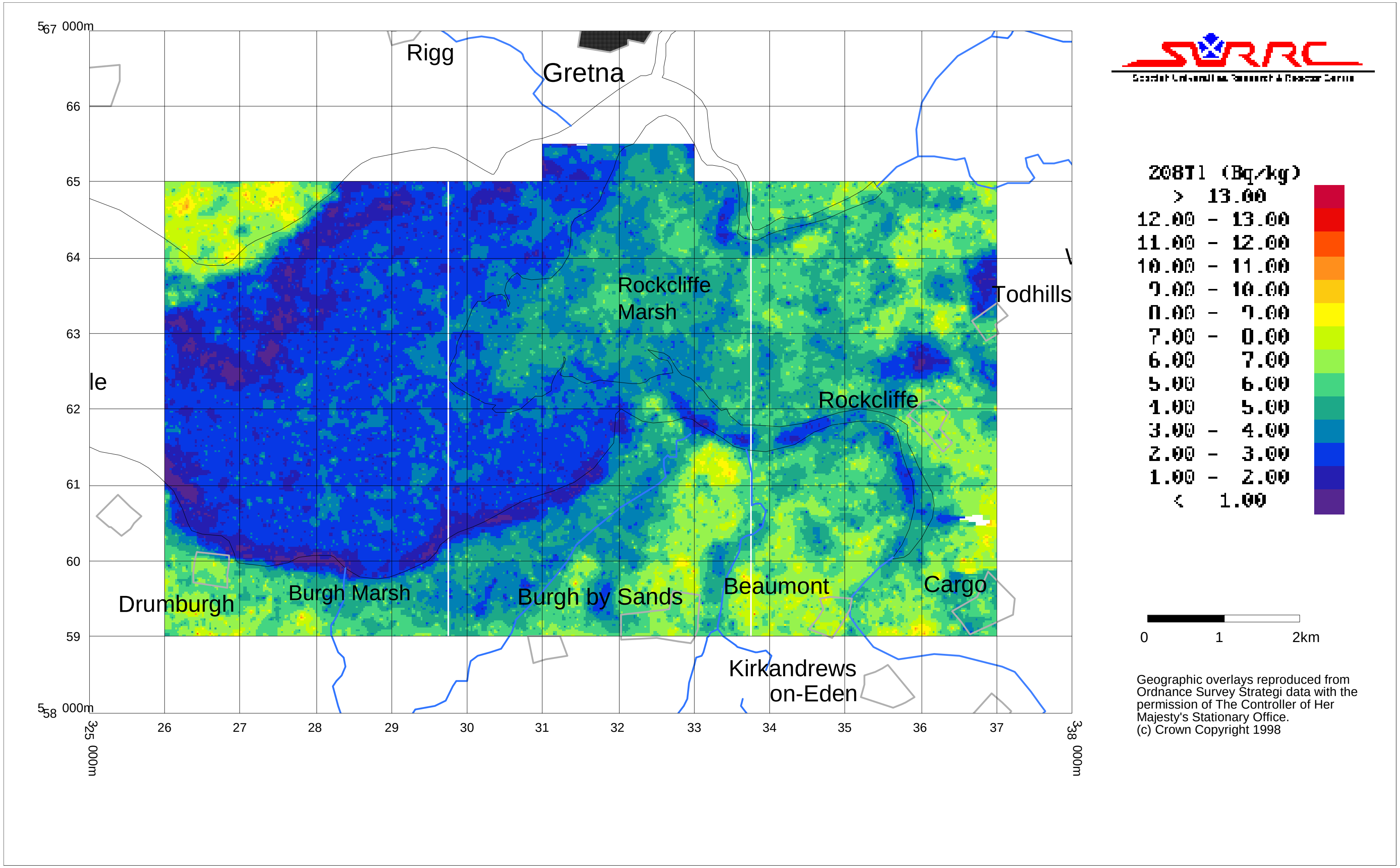

Figure 3.8: ^{208}Tl activity distribution in area A

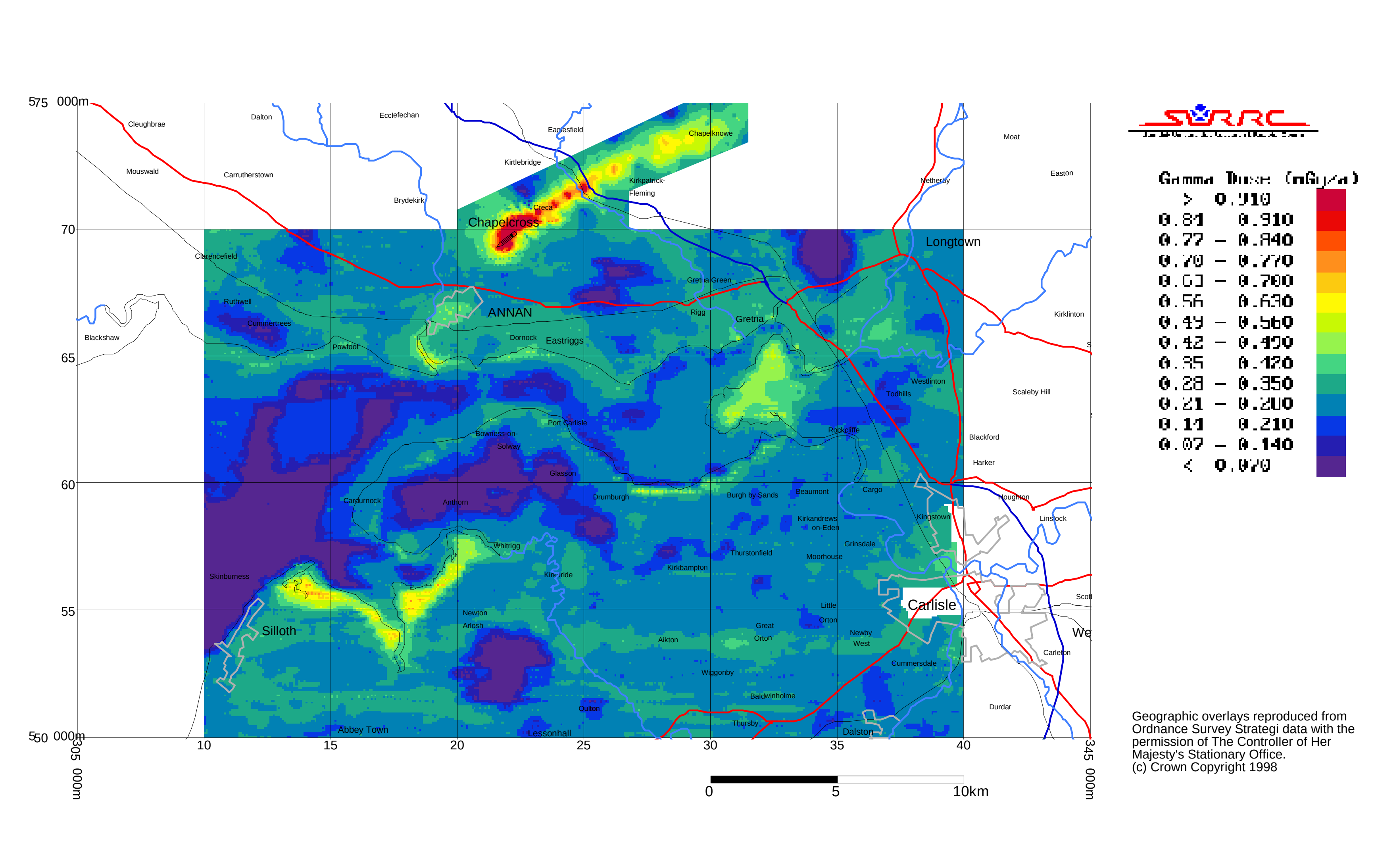

Figure 3.9: Total γ-ray dose rate distribution in area B

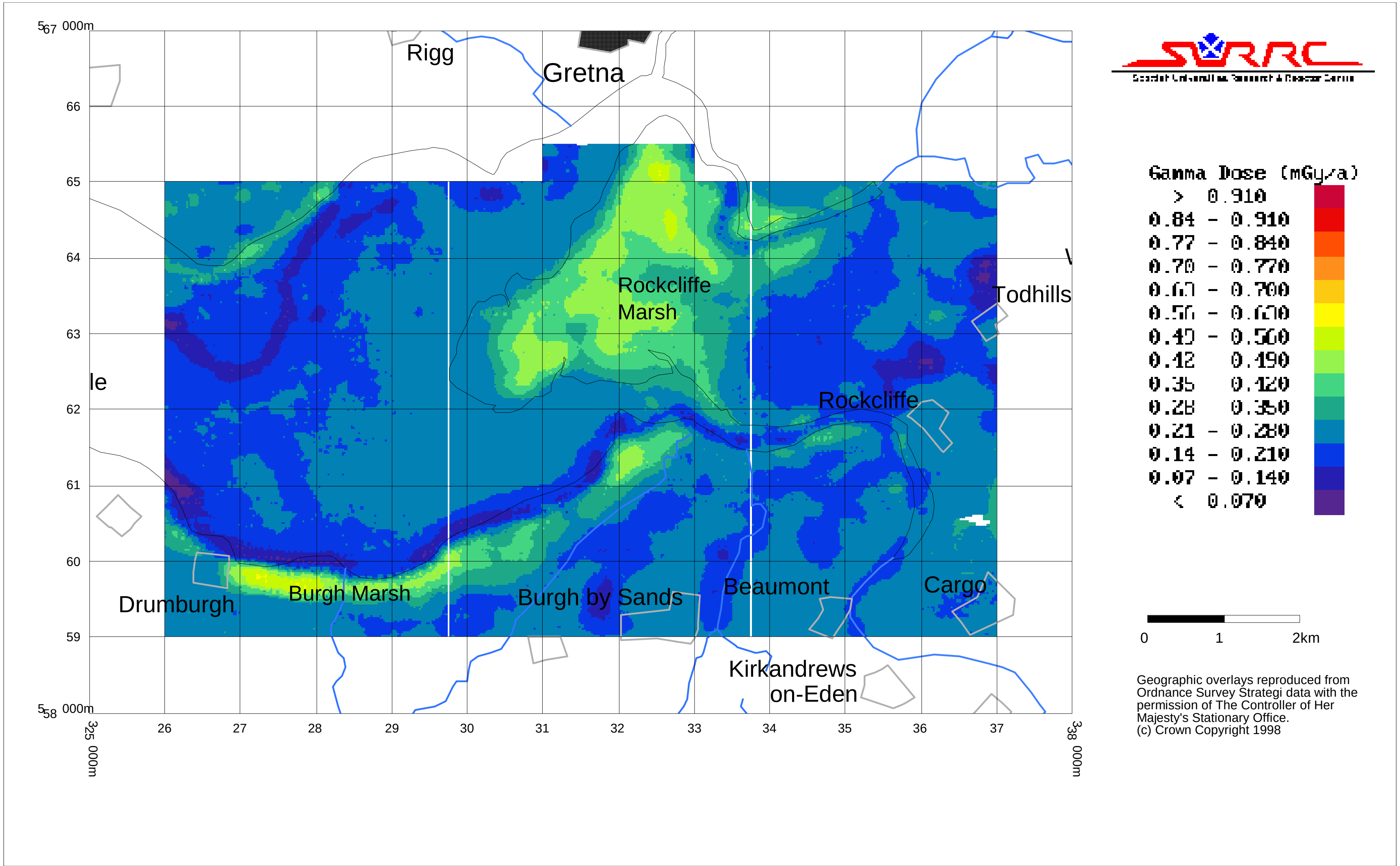

Figure 3.10: Total γ-ray dose rate distribution in area A

3.2 LoAx Data

Previous surveys of the estuarine salt marsh environments of the Solway Firth have shown significant levels of ^{241}Am (Sanderson *et al*., 1992, 1993c). A pair of externally mounted thin germanium semiconductor (LoAx) detectors were deployed during this survey, with a principle aim of investigating the potential of using such systems to map ^{241}Am distribution. Problems were experienced with the use of these detectors as a result of water penetration to HV and signal cables during the first few days, and as a consequence data from these detectors were not collected for the bulk of the survey. Data was, however, collected over the Caerlaverock calibration site, Rockcliffe Marsh and from the tie lines (although for these only one detector was operating). Analysis of this data is not yet completed, although initial analysis has shown significantly less superficial ^{241}Am at Rockcliffe than previously measured.

3.3 Remote Sensing Data

A LandSat image taken at approximately noon on the 27th April is available. The weather at this time was very good, and a quarter tile covering the survey area was later purchased to allow evaluation of possible combination of radiometric and remote sensing data. The Landsat Thematic Mapper provides 7 band spectral data from which true colour composite images and land classification maps were produced after correcting for atmospheric scatter and absorption, and applying a transformation to OS national grid using known control points. The data processing and thematic mapping of this image was conducted by P.A. Atkin and A.N. Tyler in the University of Stirling. A short report giving more details on the techniques used in the processing of the Landsat thematic mapper data is included in Appendix C.

Figures 3.11 and 3.12 show true colour composite maps for areas B and A respectively, with the corresponding thematic maps shown in Figures 3.13 and 3.14. These images clearly show various landscape features, particularly salt marshes, estuarine mud flats, peat bogs and open water. The features observed in these images correspond very well with the radiometric data. In particular, the peat wetlands are well registered and correspond to the low activity levels in the radiometrics and the land classification and boundaries of ^{137}Cs distribution in the marine interfaces demonstrate that both radiometrics and contemporary imaging give consistent information about the positions of features (eg: Burgh Marsh and river channels) in a dynamic coastal environment. The radiometrics near Burgh Marsh show the coastline to be further south than the 1998 OS digital map, the LandSat data shows the coastline to be in the same position as the radiometrics confirming that this is the result of recent erosion of the salt marsh.

The possibility of using high resolution digital photogrammetry to produce digital terrain maps and detailed land use maps was investigated. This involved mounting a digital camera inside the aircraft viewing through the lower left window bubble. Digital photographs were taken of a set of targets on the ground near Allerbeck Farm and at Caerlaverock and Rockliffe Marshes. Video images were recorded over Area A, and exploratory work in digitising these will be conducted. The angular field of view from these cameras is relatively low, and therefore the video track may not produce a complete photo mosaic of the survey area. Camera mounts designed for the digital and video cameras worked well, although some minor design modifications were noted.

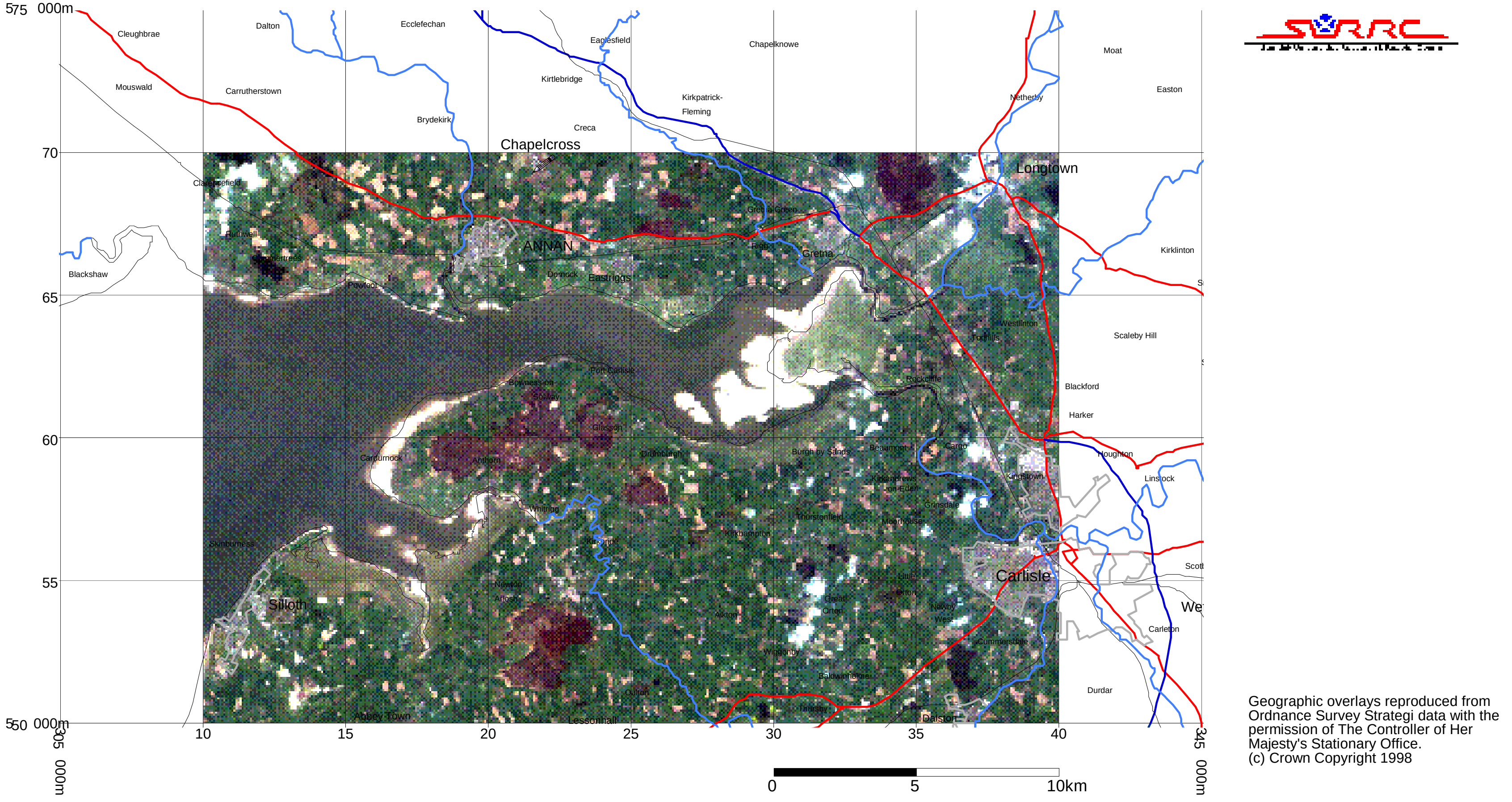

Figure 3.11: True colour composite LandSat image of area B

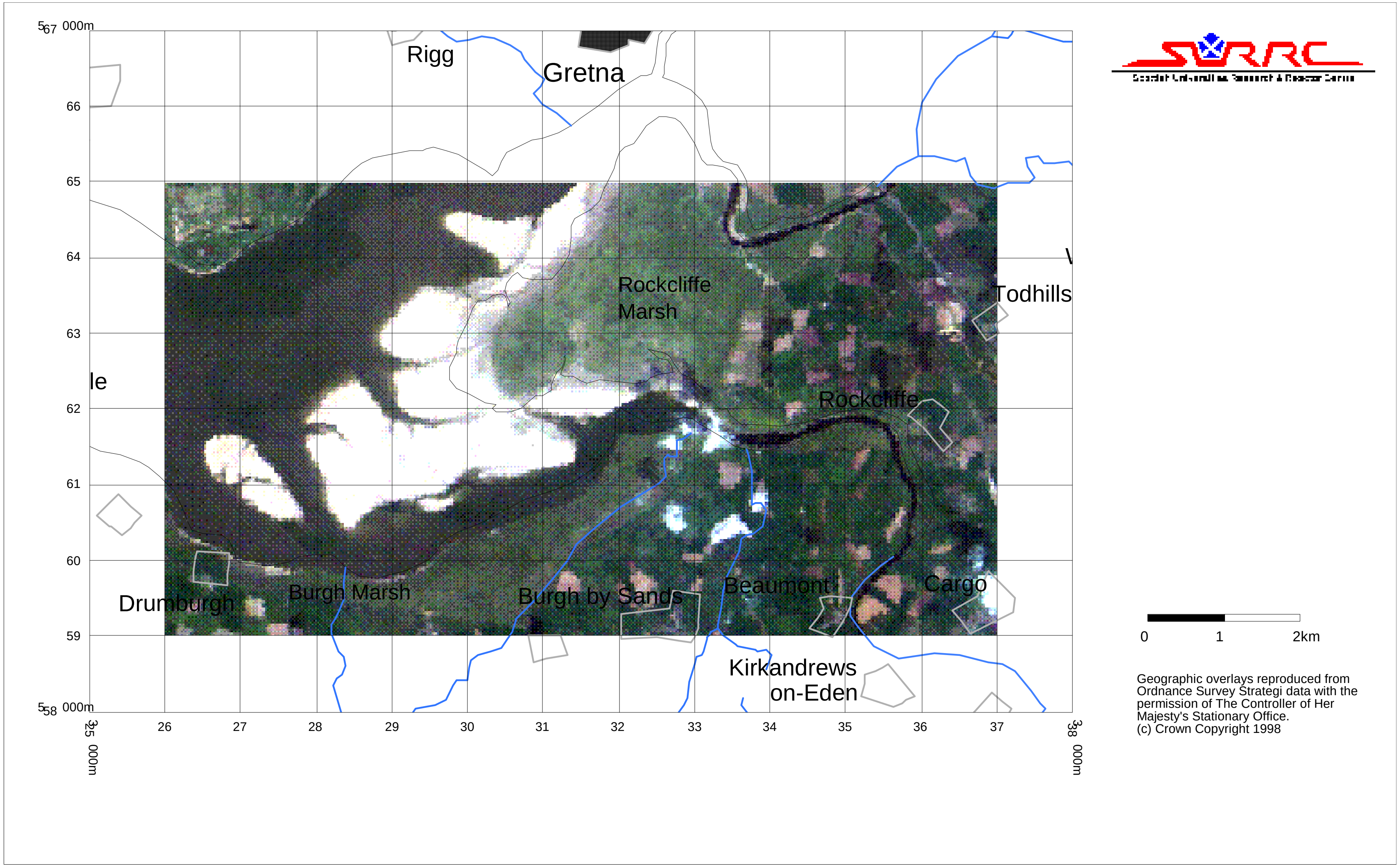

Figure 3.12: True colour composite LandSat image of area A

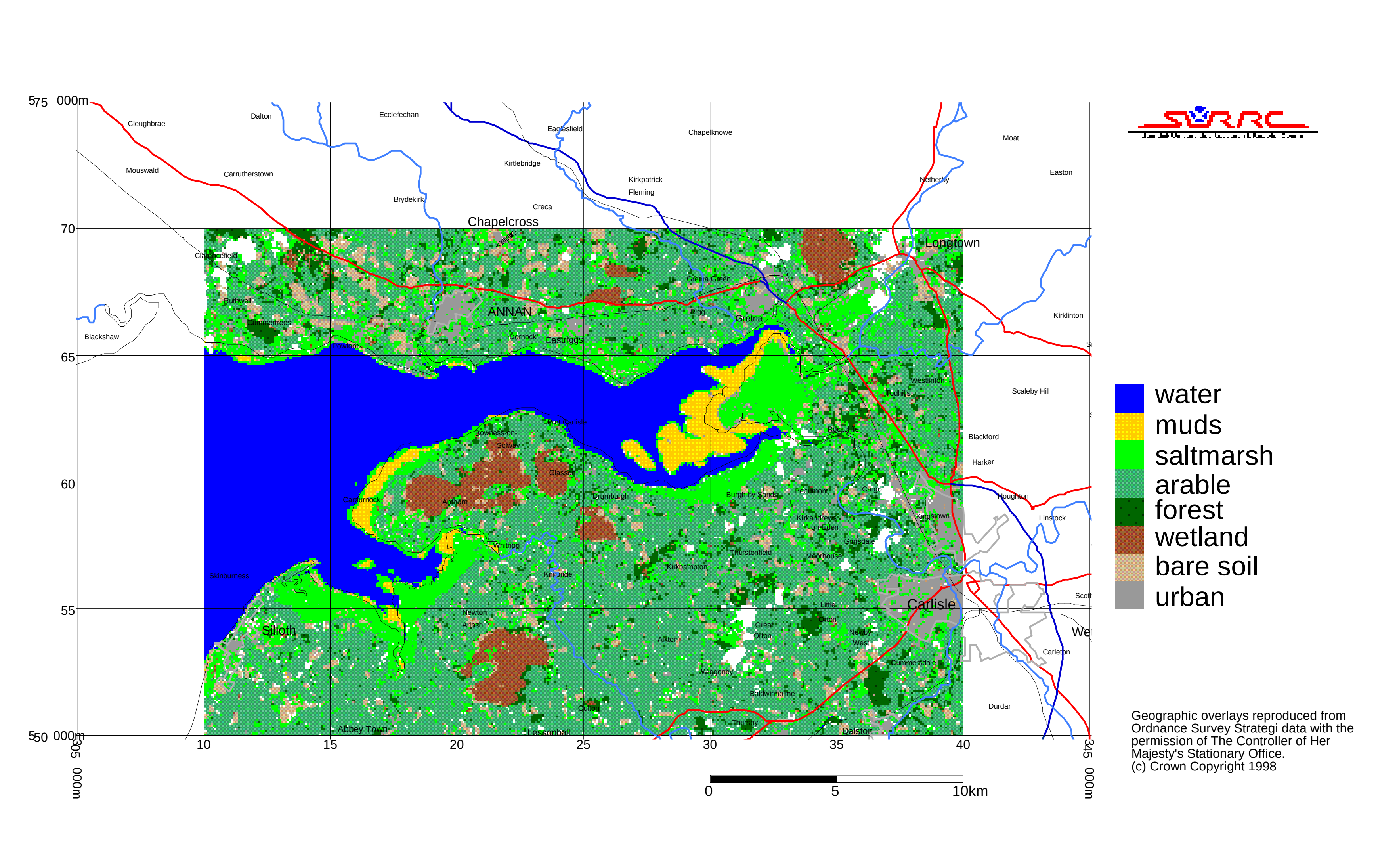

Figure 3.13: Thematic map for area B derived from LandSat data

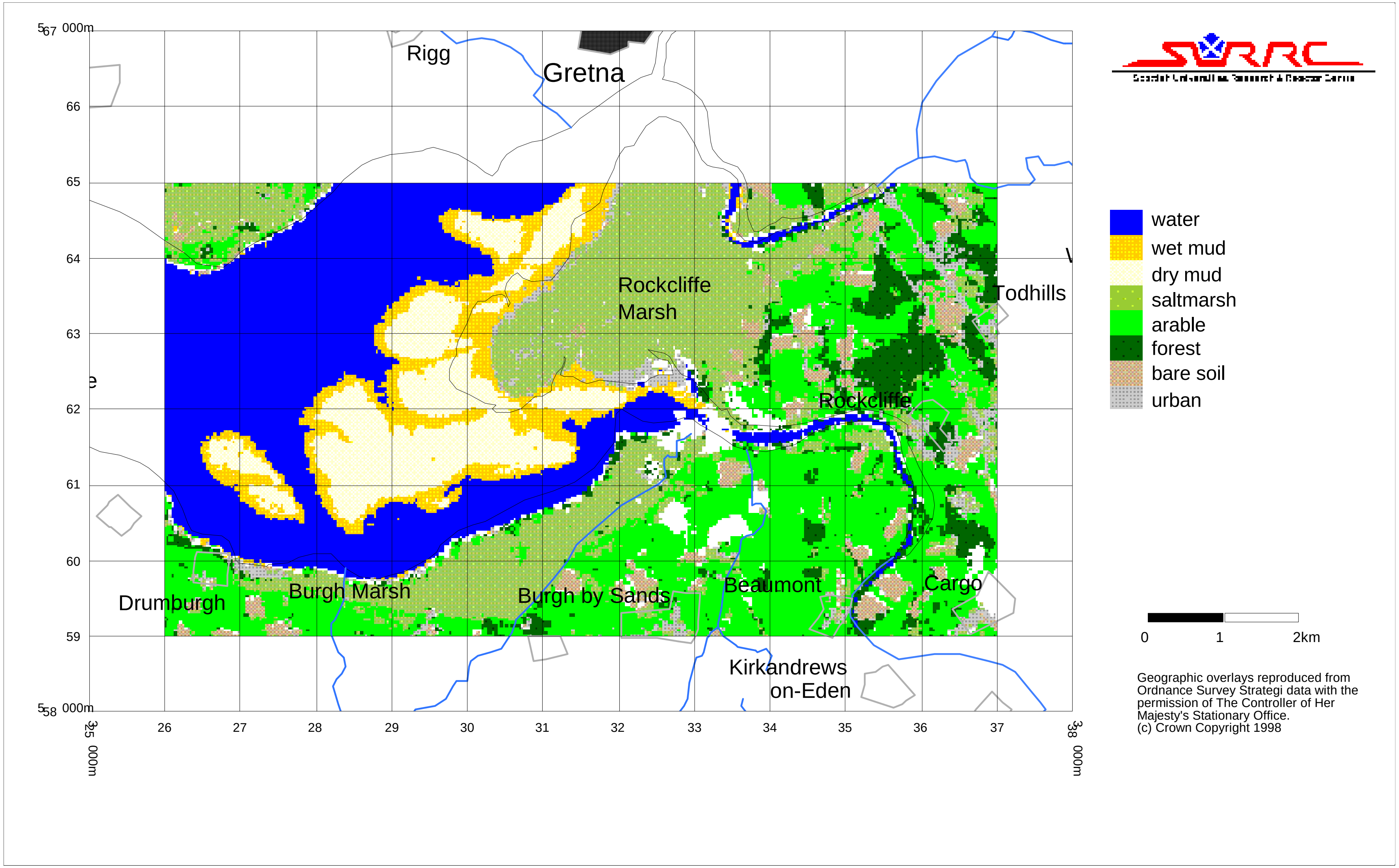

Figure 3.14: Thematic map for area A derived from LandSat data

4. CONCLUSIONS

A project to investigate the spatial and temporal influences on Airborne Gamma-ray Spectrometry (AGS) has been commissioned by the Department of the Environment, Transport and the Regions (DETR) and other organisations, with particular reference to the effects of (i) line spacing, (ii) survey ground clearance, (iii) seasonality, and (iv) environmental change. Surveys of several regions in NW England and SW Scotland are planned using a range of line spacings from 50 m to 2.5 km with subsampling of these data sets to provide data for larger line spacing. The field work has been divided into a number of phases to be undertaken under different seasonal conditions allowing evaluation of seasonal effects. The area chosen for this study exhibits a range of natural and anthropogenic radiation environments, and encompasses estuarine environments and widely differing ground terrain. Radiometric surveys of parts of the area have previously been conducted by the Scottish Universities Research and Reactor Centre (SURRC) AGS team, thus allowing evaluation of changes in the environment over an extended period. Supplementary collaborative work involving experimental assessment of digital photogrammetry and satellite imagery is also taking place within the project.

The first phase of this project involved the survey of a 20×30 km region of the Solway Firth with a 250 m line spacing, with an additional inset 6×11 km region with a 50 m line spacing around Rockcliffe Marsh. In addition, calibration manoeuvres and tie lines were flown to allow confirmation of consistency between this and later stages of field work in the project. The survey employed a 16 litre NaI(Tl) detector with supplementary measurements made with a pair of externally mounted thin Ge (LoAx) detectors. A total of 41 hours was flown on survey, with some 21300 NaI(Tl) spectra recorded with 3 s integration times, and 18700 with 2 s integration time. 5300 spectra were recorded from the LoAx detectors, 2700 of which were recorded with both detectors operating.

Gross count rates for windows in the NaI(Tl) spectra, corresponding to ^{137}Cs, ^{60}Co, ^{40}K, ^{214}Bi, ^{208}Tl and the total γ-ray dose rate, were determined for each spectrum. Backgrounds determined from measurements made over open water were subtracted, interferences between spectral components stripped out, and altitude and sensitivity calibration factors applied. Maps for the resulting calibrated distribution of ^{137}Cs, ^{40}K, ^{214}Bi, ^{208}Tl and γ-ray dose rate were produced.

^{137}Cs activities up to a few hundred kBq m^{-2} is observed on salt marsh environments, as a result of historic marine discharges from the Sellafield reprocessing plant in Cumbria. These salt marsh features had largely been observed in the 1992 Chapelcross survey (Sanderson *et al.*, 1992). However, there are some differences compared to the earlier data; in particular Burgh Marsh has significantly eroded, Rockcliffe Marsh and salt marshes near Annan are more pronounced, and small features register better primarily due to the higher spatial resolution of this survey.

The distribution in the environment of ^{40}K, ^{214}Bi and ^{208}Tl reflect local geology and soils, with relatively high levels of ^{40}K on estuarine mud and very low levels of all these naturally occurring radionuclides over the peat wetlands.

Uncorrected interferences from ^{41}Ar and ^{16}N gaseous discharges from the Chapelcross power station results in apparently high ^{40}K, ^{214}Bi and ^{208}Tl activity in the immediate vicinity of the plant.

There are relatively high levels of ^{214}Bi associated with some railway sidings to the northwest of Carlisle, probably relating to the use of material enhanced in uranium, for example industrial slag, in the construction of the line.

Gaseous radon is a precursor for ^{214}Bi, and the high mobility of this gas can lead to local disequilibria. Difficulties were experienced during this survey with correctly accounting for the effects of radon migration on some days.

Apart from the Chapelcross signals, the highest dose rates are from the ^{137}Cs contaminated salt marshes, particularly around Moricambe Bay to the NE of Silloth. The wet peat areas, which were observed to have very low natural activity levels, have very low dose rates similar to background levels over open water.

The higher resolution survey has produced maps with much greater spatial resolution, easily identifying features with spatial dimensions of 50 m, compared to 200 m for the lower resolution survey data. The higher resolution data clearly shows river channels, and small streams and standing water on the salt marshes. Compared with earlier surveys the salt marshes near Annan are much more pronounced, possibly due to the closer line spacing of this survey picking up these relatively small features, and Burgh Marsh has noticeably eroded.

True colour composite and thematic maps have been produced from LandSat TM data for this area. The features observed in these images correspond very well with the radiometric data. In particular, the radiometrics for Burgh Marsh show a coast line south of the position given by 1998 OS digital map data. The satellite imagery shows the coast line in the same location as the radiometrics, confirming that this section of coast line has eroded considerably in recent years.

Additional survey work during summer conditions will involve a re-flight over area A at 250 m line spacing, and surveys of additional large areas at 500 m and 2.5 km line spacing, along with re-flying of the tie lines.

Following completion of the survey tasks, quantitative comparisons between the data sets will be conducted along with a more complete analysis of the effect of line spacing. Comparison with earlier data sets will involve recalibration of the earlier data and resampling of the current data set to match the earlier line spacing, which will allow the evaluation of temporal changes over several years. The tie line and area A data will allow the evaluation of seasonal differences. The data set will be used to simulate data sets with wider line spacings, and inventory calculations will be used to quantify the effect of increased line spacing.

ACKNOWLEDGEMENTS

The project was commissioned by the Department of the Environment, Transport and the Regions (DETR), with the Environment Agency (EA) and Ministry of Agriculture, Fisheries and Food (MAFF) as co-sponsors. Additional funding was also provided by SNIFFER, IMC, and BNFL Magnox. The support given by Kenneth Nulty and Malcolm Wakerley of DETR in initiating this project and coordinating support from the other agency is appreciated.

We are grateful to PDG Helicopters for their support with aircraft engineering, operations and support including arranging for CAA permission to conduct the survey. We are particularly grateful to John Constable and Ivor Griffiths for flying the aircraft accurately at low altitude. We are also grateful to H.J. Hickinson & Son Ltd for help in the design and development of mounting apparatus for the survey equipment.

We are grateful to British Nuclear Fuels Ltd (BNFL), Chaplecross Nuclear Power Station, particularly to Jenie Dutton for arranging permission from the Civil Aviation Authority (CAA) to fly within the exclusion zone up to the perimeter fence of the power station.

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APPENDICES

Appendix A: Summary of Detector Calibration and Data Processing

1) Detector and Data Collection System

16 litre NaI(Tl) detector array (4 crystal pack):
Serial numbers: IA510, JA894, IV43, HR762
EHT: 1000V (nominal)

Pair of thin Ge semiconductor (LoAx) detectors operated in parallel with scintillation detector:
Serial number: 32-TN20699B (EHT: -2500V)
Serial number: 32-TN30706C (EHT: -3000V)

Date	Resolution at 661 keV (%)	Gross ^{137}Cs count rate	Net ^{137}Cs count rate
20/4/1999	10.0		1590
21/4/1999	9.5	2403	1708
22/4/1999	9.3	2476	1872
23/4/1999	9.2	2498	1892
24/4/1999	9.6	2215	1706
25/4/1999	9.5	2194	1711
26/4/1999	9.3	2198	1679
27/4/1999	8.8	2232	1694
28/4/1999	9.1	2119	1563

Table A.1: 16 litre NaI(Tl) detector daily performance check

Filename	Filenumber	Date	Counting times (s)
DETB1	1,869	20/4/1999	3
DETB2	1,700	20/4/1999	3
DETB4	1,170	21/4/1999	3
DETB5	1,112	21/4/1999	3
DETR6	1,668	21/4/1999	3
DETB7	1,999	21/4/1999	3
DETB8	1,967	22/4/1999	3
DETB9	1,235	22/4/1999	3
DET10	1,999	22/4/1999	3
DET11	1,63	22/4/1999	3
DET12	1,104	22/4/1999	3
DET13	1,301	23/4/1999	3
DET14	1,499	23/4/1999	3
DET15	1,626	23/4/1999	3
DET16	1,956	24/4//1999	3
DET17	1,156	24/4/1999	3
DET18	1,539	24/4/1999	3
DET20	1,176	24/4/1999	3
DET21	1,999	25/4/1999	2
DET22	1,233	25/4/1999	2
DET23	1,124	25/4/1999	2
DET24	1,999	25/4/1999	2
DET25	1,563	25/4/1999	2
DET26	1,999	26/4/1999	2
DET27	1,999	26/4/1999	2
DET28	1,442	26/4/1999	2
DET29	1,856	26/4/1999	2
DET31	1,223	26/4/1999	2
DET32	1,675	27/4/1999	3
DET33	1,995	27/4/1999	2

Filename	File numbers	Date	Counting times (s)
DET35	1,134	27/4/1999	2
DET36	1,143	27/4/1999	2
DET37	1,806	27/4/1999	2
DET38	1,809	27/4/1999	2
DET39	1,43	27/4/1999	2
DET40	1,150	28/4/1999	3
DET41	1,105	28/4/1999	3
DET42	1,574	28/4/1999	3

Table A.2: Summary of survey files

Window	Radionuclide	Channel range
1	^{137}Cs (661 keV)	95-128
2	^{60}Co (1172 keV)	170-208
3	^{40}K (1461 keV)	220-270
4	^{214}Bi (1764 keV)	270-318
5	^{208}Tl (2615 keV)	390-480
6	Total > 450 keV	75-500

Table A.3: Spectral windows for NaI(Tl) detector

	^{137}Cs	^{60}Co	^{40}K	^{214}Bi	^{208}Tl
^{137}Cs	1	0.001	0	0	0
^{60}Co	0.411	1	0.241	0.04	0.02
^{40}K	0.594	0.483	1	0	0
^{214}Bi	3.657	1.741	1.05	1	0.04
^{208}Tl	2.681	0.644	0.706	0.438	1

Table A.4: Stripping ratios measured April 1999

Window	Radionuclide	Exponential Altitude Coefficient	Slope of Calibration Line	Calibration Intercept
1	^{137}Cs	0.0133	0.282	0.0
2	^{60}Co	0.01	1.0	0.0
3	^{40}K	0.0109	6.767	0.0
4	^{214}Bi	0.00883	3.164	0.0
5	^{208}Tl	0.00898	0.4715	0.0
6	γ-dose rate	0.0107	0.0007	0.0

Table A.5: Calibration Constants

Appendix B: Summary of Core Scanning Results

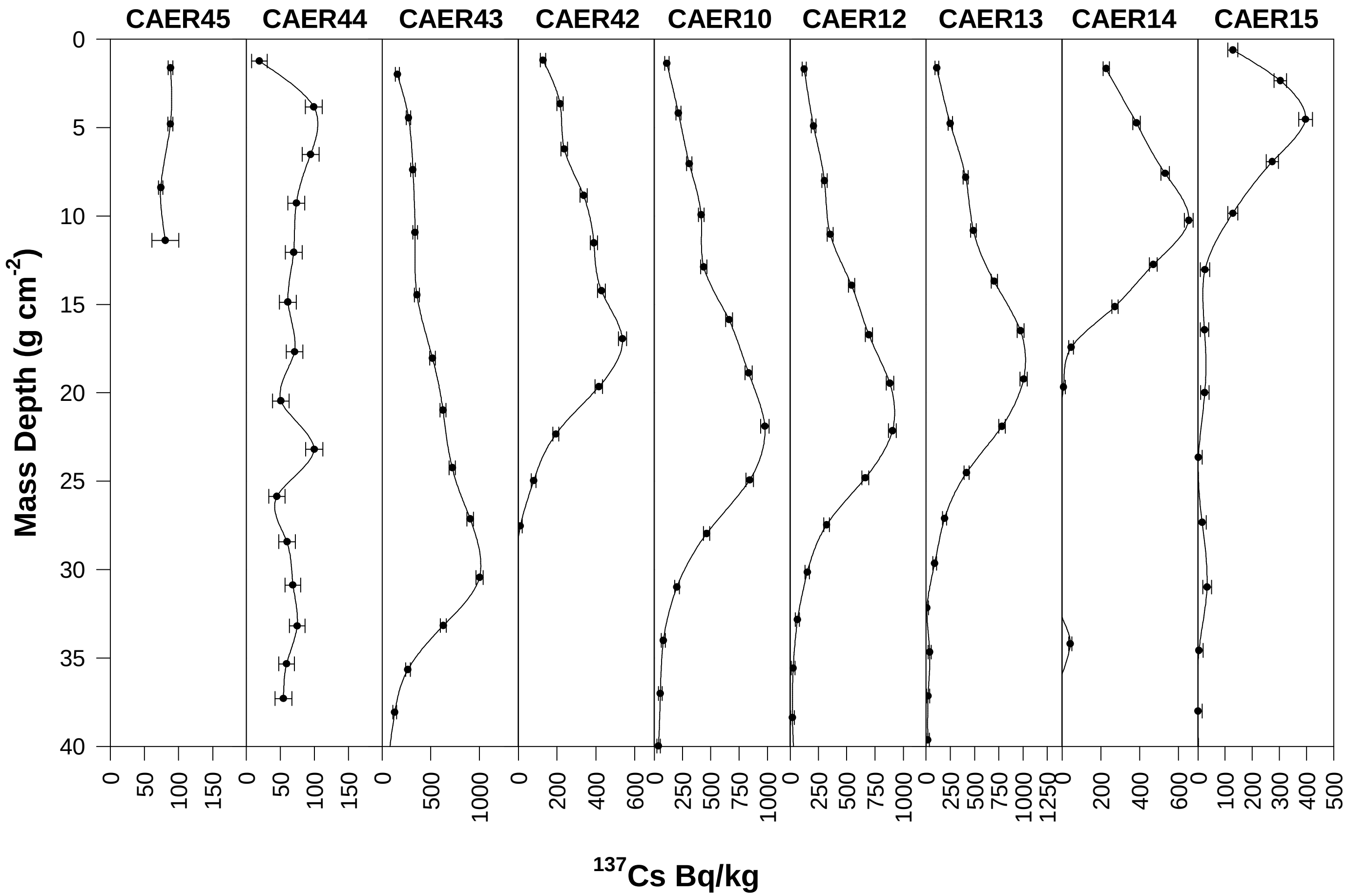

Figure B.1: ^{137}Cs depth profiles for the north-south transect

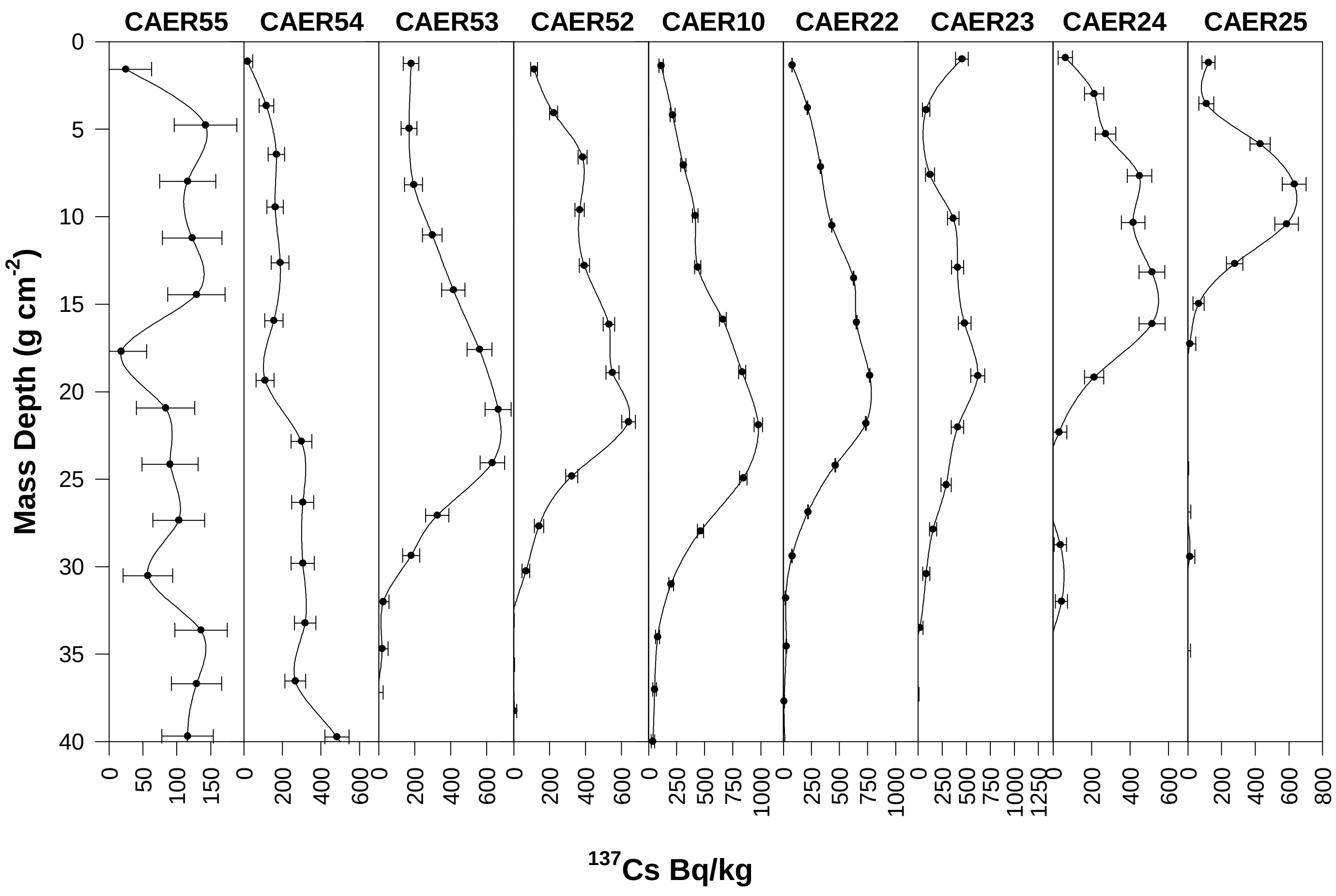

Figure B.2: ^{137}Cs depth profiles for the north east-south west transect

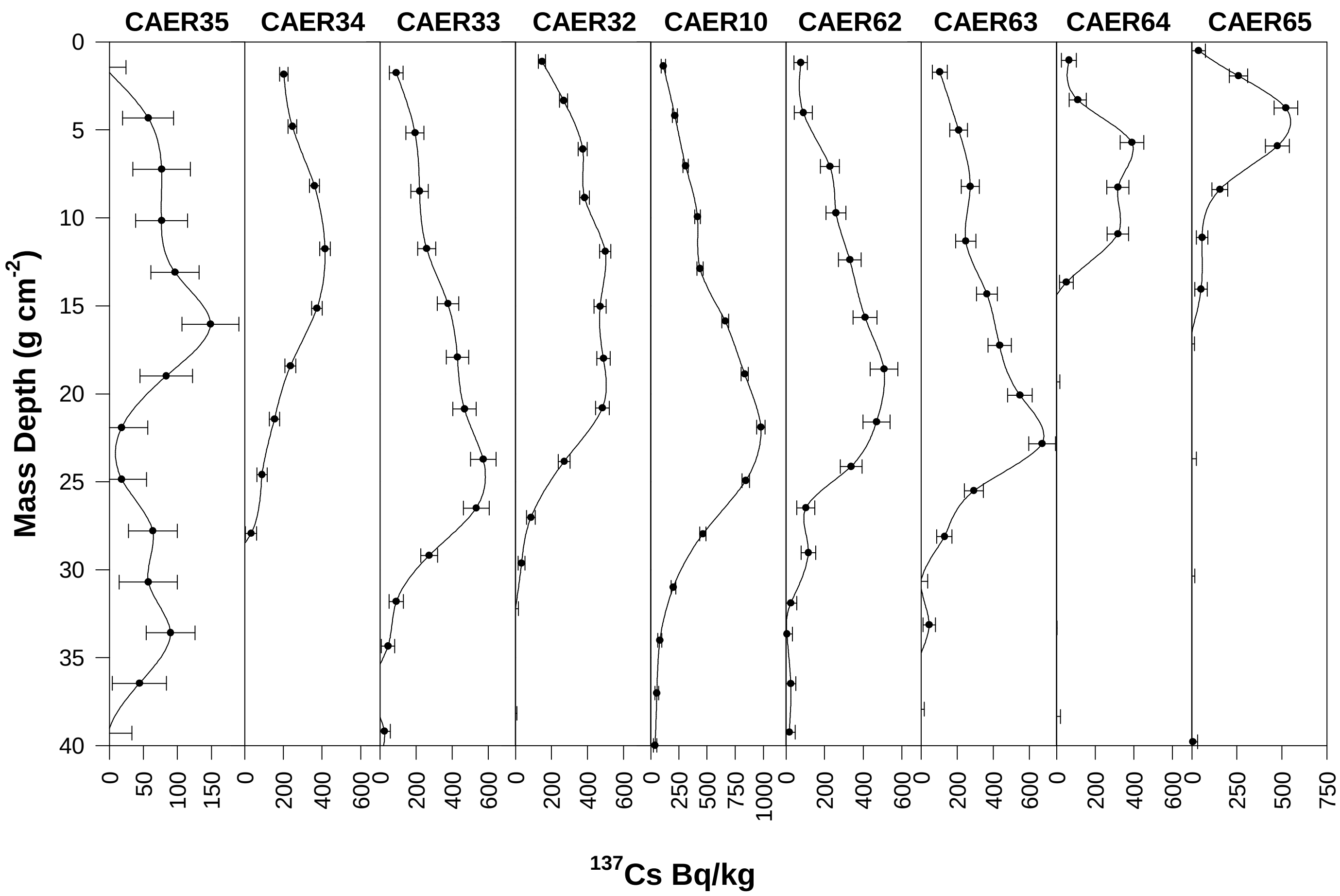

Figure B.3: ^{137}Cs depth profiles for the south east-north west transect

Radial		Shell				
		0 (Centre)	2 (8m)	3 (32m)	4 (128m)	5 (256m)
1	Mean Mass Depth (g cm^{-2})	19.0	18.6	16.8	9.2	4.9
	Surface Activity (kBq m^{-2})	113.8±6.3	100.5±2.4	104.5±12.8	48.1±2.1	18.1±4.5
2	Mean Mass Depth (g cm^{-2})		16.8	15.4	11.1	8.5
	Surface Activity (kBq m^{-2})		88.7±2.9	66.1±4.0	47.5±4.4	34.2±1.1
3	Mean Mass Depth (g cm^{-2})		13.8	19.5	12.1	18.8
	Surface Activity (kBq m^{-2})		67.1±1.2	71.1±2.9	46.9±1.1	14.3±4.9
4	Mean Mass Depth (g cm^{-2})		13.4	23.2	19.6	
	Surface Activity (kBq m^{-2})		52.6±19.3	132.5±3.3	15.2±5.1	
5	Mean Mass Depth (g cm^{-2})		15.8	18.1	31.0	23.7
	Surface Activity (kBq m^{-2})		73.4±1.3	77.1±4.8	85.2±3.2	27.0±13.8
6	Mean Mass Depth (g cm^{-2})		17.0	17.3	7.6	5.0
	Surface Activity (kBq m^{-2})		56.3±6.5	64.2±2.2	20.6±1.9	20.3±5.8
Mean	Mean Mass Depth (g cm^{-2})	19.0	15.9±0.8	18.4±1.1	15.1±3.6	12.2±3.5
	Surface Activity (kBq m^{-2})	113.8±6.3	73.1±7.6	85.9±11.1	43.9±10.2	22.8±3.2
Weighting for 100m (%)			4.7	41.7	44.2	9.4

Table B.1: ^{137}Cs mean mass depth and surface activity for cores from Caerlaverock calibration site.

Appendix C: The Processing of Landsat Thematic Mapper Data

A.N. Tyler, P.A. Atkin. Department of Evironmental Science, University of Stirling

C.1 Introduction

The Landsat Thematic Mapper is one of a series of optical remote sensing instruments mounted on satellite platforms. The Landsat TM 5 satellite, launched in 1984, follows a sun-synchronous, near polar orbit 705 km above the Earth with a sixteen-day repeat frequency. On launch Landsat TM 5 was placed eight days out of phase with TM 4 giving a possible repeat frequency of 8 days. The area imaged by the sensor is a 185 km swath with a spatial resolution of 30 m for bands 1 to 5 and 7 and 120 m for band 6. The details of these bands are given in Table C.1.

Band	Wavelength (μm)	Spectral Location	Designed for the application of...
1	0.45-0.52	Blue	Water penetration, soil-vegetation discrimination and forest mapping.
2	0.52-0.60	Green	Green vegetation reflectance peak detection and vegetation vigour assessment.
3	0.63-0.69	Red	Chlorophyll absorption region aiding plant species identification.
4	0.76-0.90	Near IR	Vegetation type, vigour and biomass and water body delineation.
5	1.55-1.75	Mid IR	Vegetation moisture content and separation of snow and cloud cover.
6	10.4-12.5	Thermal IR	Vegetation stress analysis and thermal mapping
7	2.08-2.35	Mid IR	Discrimination of rock and mineral types and possible vegetation moisture content.

Table C.1: The details of the Landsat TM 5 spectral scanner.

The quarter scene of TM data obtained on the 27th April 1999 was provided by the European Space Agency's remote sensing department, Eurimage in the standard ESA format. This eight bit data is pre-geometrically registered in decimal degree co-ordinates. The image was then imported into the ERDAS image processing system, which allowed the boundary co-ordinates to be determined and a basic image assessment possible.

C.2 Atmospheric Correction

For each pixel the radiance received by the sensor will be made up of the radiance of the surface observed and radiance caused by both atmospheric scatter and absorption. The increased radiance due to atmospheric scatter is wavelength dependent and is predominant at the shorter wavelengths with the effects decreasing with increasing wavelength. Atmospheric absorption decreases radiance and the effects are generally less significant than scattering. The effect is predominant in wavelengths of near infra-red and above. For the true surface radiance to be utilised these atmospheric effects must be removed. There are various atmospheric correction techniques in use ranging from the simple first order haze corrections to the complex radiative transfer models such as LOWTRAN and 5S. The complex models are not always the most accurate as additional *in-situ* atmospheric data inputs are required. In the absence of such information estimates must be made which may actually cause larger errors than they remove.

For this reason, a simple first order atmospheric correction was applied to the image using the standard darkest pixel subtraction technique. This technique relies on the fact that the reflectance from a dark surface, such as deep clear water, is essentially zero. Thus any reflectance from these dark surfaces is assumed to be due to atmospheric scattering effects such as path radiance, this value is then subtracted from all pixels. The main assumption of this technique is that the atmospheric effects are uniform across the scene, which may or may not be valid depending on the individual scene.

C.3 Geometric Correction

For the Landsat TM data to be combined with the airborne gamma spectrometry data, both data-sets must be in the same geographical co-ordinates. Thus the Landsat TM data needed to be converted from the decimal degrees of the universal transverse mercator projection (UTM) to the Ordnance Survey (OS) national grid co-ordinates in meters. A manual geocorrection technique was employed using known ground control points to anchor the image into the required co-ordinate system. This was accomplished using 98 ground control points derived from the OS Landranger (1:50000) series of maps measured to the nearest 0.5 mm, giving an measurement error of 25 m. The image was re-projected using nearest neighbour resampling to give a spatial resolution of 35 m. Subsets A and B were then produced covering the areas of interest as detailed in table C.2.

Area		Upper Left Co-ordinate (OS NG)	Lower Right Co-ordinate (OS NG)
A	Rockcliff & Burgh Marshes	326000, 565000	337000, 559000
B	Inner Solway Firth	310000, 570000	340000, 550000

Table C.2: The areas subset from the quarter scene Landsat TM image

C.4 Land Classification

The objective of land classification of an image is to automatically categorise all the image pixels into land cover classes. There are two main methods of classification, unsupervised and supervised. In an unsupervised classification the user specifies the number of classes the data is to be categorised into but allows the software to make the decisions regarding which pixels are in which class. A commonly used method of ensuring two similar classes are not confused is to make the software think that there are far more surface types than there really are. The various classes can then be merged later to form the correct number of classes. To avoid this problem a supervised classification allows the user greater control to choose pixels and define the class to which they belong. The classifier then looks for similarities between each pixel and the user specified pixels. Both unsupervised and supervised classifications were tested, with the supervised maximum likelihood classifier giving a better result. The classes chosen are summarised in table C.3.

Classes used in subset A	Classes used in subset B
Cloud	Cloud
Water	Water
Wet mud/sand	Mudflat
Dry mud/sand	Saltmarsh
Saltmarsh	Arable
Arable	Bare soil
Bare soil	Wetland
Urban	Forest
	Urban

Table C.3: Land cover classes used in the classification of subsets A and B.

It is worth noting that in both subset images the saltmarsh was the most difficult surface type to classify. The classifier correctly assigned all the saltmarsh to the correct class but also assigned other variable surface types such as scrubby wasteland to the saltmarsh class. The classification of bare soil, mudflat and wetland were particularly successful.

C.5. Digitisation of Vectors

To allow the location of the land cover types to be overlaid onto the airborne gamma spectrometry data the surface type information was converted to vector data. This was done visually from the Landsat TM data. When digitising from raster data consideration must be given to the occurrence of mixed pixels. These occur along the boundaries of land cover types where the pixel contains spectral signature from more than one land cover type. For this exercise it was decided to include only pure pixels within the vector area. The consequence of this is that the vectors of adjacent land cover surfaces may not lie directly adjacent to each other. However, any surface types causing anomalies in the airborne gamma spectrometry data will be easily identified. The vectors created in ERDAS were exported as .DXF files, the co-ordinate details of which are given in table C.4.

Boundary Box Co-ordinates (UK National Grid, m)				
Feature	X-minimum	X-maximum	Y-minimum	Y-maximum
A-Coast	325691	336215	558824	565200
A-Mud	326346	332327	560358	565166
A-Saltmarsh	327277	335368	559006	565199
B-Coast	309278	334084	552530	566714
B-Mud	309422	334408	552375	566512
B-Saltmarsh	312195	335740	551510	566494
B-Wetland	317394	336159	550740	570596

Table C.4: The boundary box co-ordinates of the .DXF vector files.